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THESIS

A CSMP COMMUTATION MODEL FOR DESIGN STUDY OF A BRUSHLESS DC MOTOR POWER CONDITIONER FOR A CRUISE MISSILE FIN CONTROL ACTUATOR

by

Peter Norman MacMillan

June 1985

Thesis Advisor: A. Gerba

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A CSMP Commutation Model for Design Study of a Brushless DC Motor Power Conditioner for a Cruise Missile Fin Control Actuator

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ABSTRACT

Recent improvements in rare earth magnets have made it possible to construct strong, lightweight, high horsepower DC motors. This has occasioned a reassessment of electromechanical actuators as alternatives to comparable pneumatic and hydraulic systems for use as flight control actuators for tactical missiles. A dynamic equivalent circuit model for the analysis of a small four pole brushless DC motor fed by a transistorized power conditioner utilizing high speed switching power transistors as final elements is presented. The influence of electronic commutation on instantaneous dynamic motor performance is particularly demonstrated and good correlation between computer simulation and typical experimentally obtained performance data is achieved. The model is implemented in CSMP language and features improvements in transistor and diode models as well as a more accurate air gap flux representation over previous work. Hall effect sensor rotor position feedback is simulated. Both constant and variable air gap flux is modeled, and the variable flux model treats the flux as a fundamental and one harmonic.

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I. INTRODUCTION

Electronically commutated brushless DC motors are increasingly becoming practical for numerous applications. The advantages of these motors over conventional brush-type DC motors are smaller size and lighter weight per horsepower. The increase in power over conventional DC motors is realized by the use of three phase circuitry commonly found in synchronous AC motors which results in additional motor current-magnetic flux interaction not available with conventional DC motor designs. The elimination of the brush commutation and rotating armature allows operation at higher speed with higher currents and improves the thermal characteristics of the motor as heat generating windings will be contained in the stator which can be more efficiently cooled.

In this thesis, an equivalent circuit motor-power conditioner modeling approach is used to predict the dynamic performance of a typical brushless DC motor for a fin control actuator assembly. The interaction of the power conditioner final drive elements with the stator currents is demonstrated in addition to the rotor magnetic flux - stator current interaction and interdependence. Numerical results of steady state operation are compared with experimentally obtained instantaneous voltages and currents in amplitude and in profile. After demonstration of steady state operation of the model, start-up and reversal transients are predicted.

The model developed in this thesis is part of a continuing program to develop a comprehensive simulation for a fin control actuating system which has been the subject of previous work [Ref. 1 and 2] and is subject to further development.

The object of this thesis is to extend previous work on brushless DC motors [Ref. 1] to include switching characteristics of power transistors and diodes in such a manner as to provide a coherent model of power conditioner final drive elements and a brushless DC motor. Additionally, the simulation provides steady state as well as instantaneous dynamic performance during start-up and sudden reversal of the motor. The IBM Continuous System Modeling Program (CSMP) was chosen primarily because of the inherent attributes of CSMP for modeling dynamic physical systems. Inasmuch as previous model development utilized this language, some continuity of development is maintained.

II. SYSTEM DESCRIPTION

A. SYSTEM BLOCK DIAGRAM

The simulation diagram for the model is depicted in Figure 2.1 and demonstrates the interrelation between the magnetic flux model, the torque coefficient, and the generated back emf voltage. The nonlinear nature of the generated voltage and torque is indicated by the multipliers in the diagram for angular speed times the magnetic flux, $W(t)\Phi(t)$, used in the back emf calculation and the motor current times the magnetic flux, $I(t)\Phi(t)$, used in the generated torque calculation. The three phase electrical simulation calculates three phase currents, which are multiplied by the torque coefficient and normalized flux model for each phase resulting in a torque due to the current in each phase. The motor torque is the sum of the three phase torques, and the net torque is the motor torque less the load torque. Motor rotation is then calculated by applying the net torque to the rotor inertia and viscous friction. The integral of the rotor angular speed is calculated for angular position, which is fed to the flux and transistor logic models to control the generation of conduction currents for each phase. The transistor model and magnetic flux model are discussed in Chapter Three and Chapter Four, respectively.

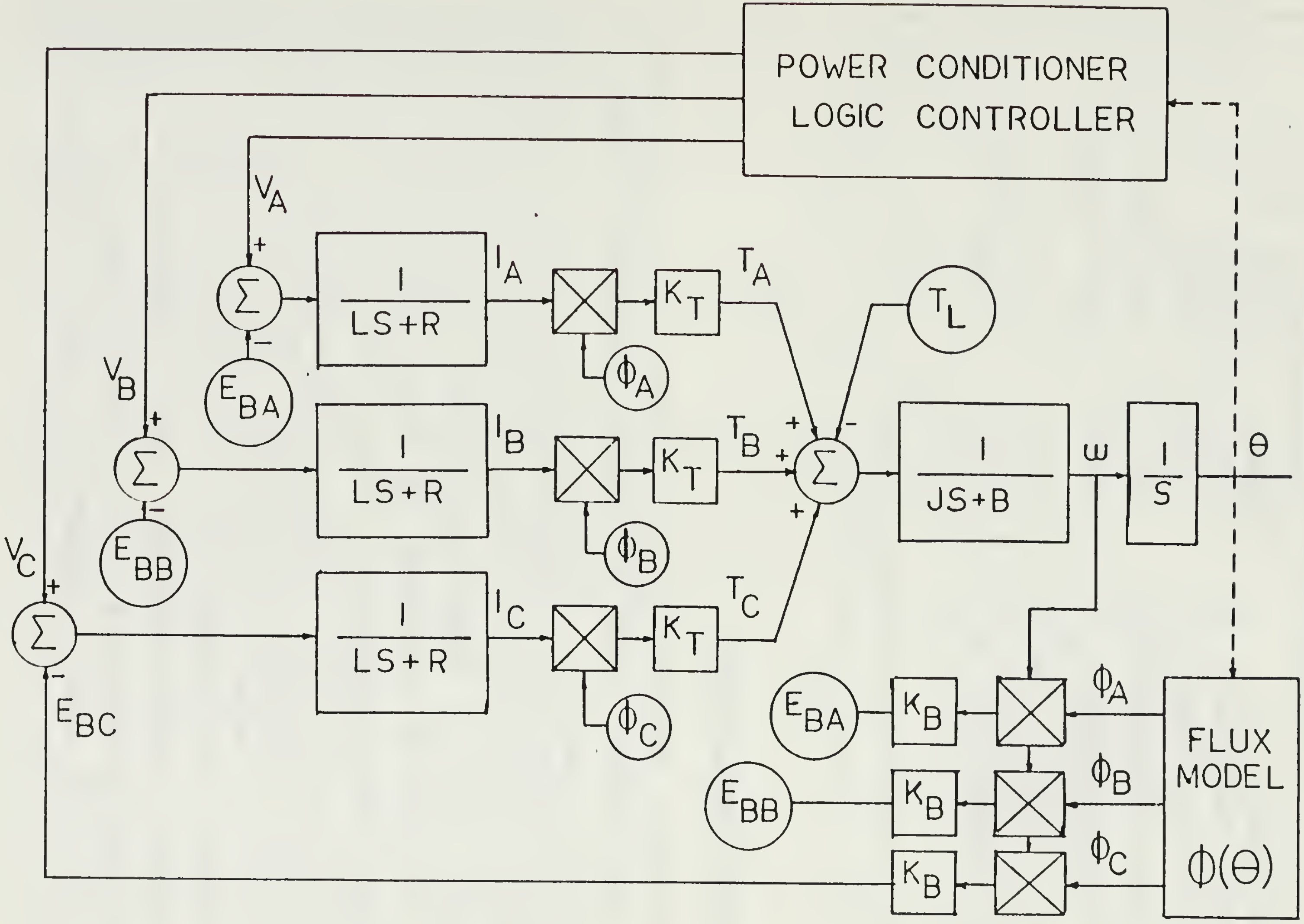


Figure 2.1 Motor and Power Conditioner Simulation Diagram

TABLE I

Typical Motor Parameters

Parameter	Value	Units
Stator resistance, Ra	1.37	Ohms
Stator Inductance, La	0.0016	Henrys
Torque coefficient, Kt	15.9	Oz-In/amp
Reverse voltage coefficient, Kb	0.112	Volt-Sec/Rad
Rotor inertia, Jm	0.001	Oz-In/Sec
Viscous friction coefficient, Bm	0.022	Oz-In-Sec/Rad

B. MOTOR CONFIGURATION

The motor simulated in this thesis is a three phase, four pole device typical of modern brushless DC motors as described in [Ref. 1]. Typical values for the motor parameters are contained in Table I. The listed values of resistance and inductance are as measured across two windings as the motor is only a three wire device as pictured in Figure 2.2. It should be noted that the motor inertia is very low; a typical rotor diameter is of the order of one inch and results in a very small mechanical time constant. A transverse cross sectional view of rotor and stator for a the model motor is shown in Figure 2.3, with the rotor in the zero (or 180) degree position. The magnetic rotor can be seen to have north and south poles separated by ninety degrees. This generates a flux distribution which alternates polarity every ninety mechanical degrees as depicted in

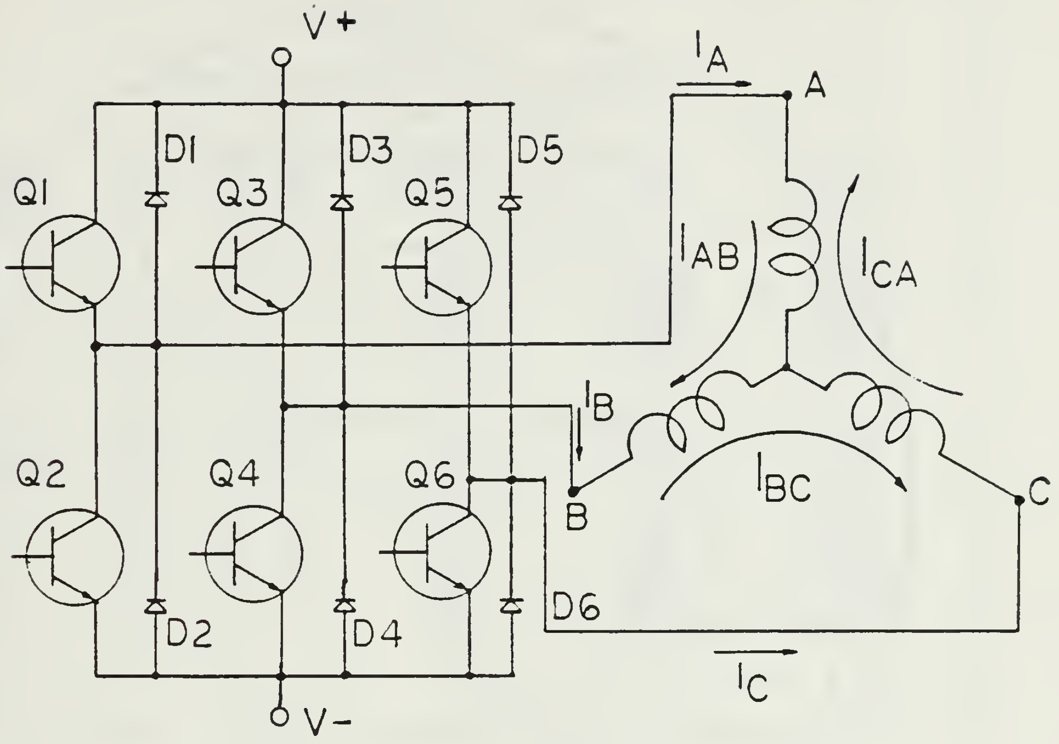


Figure 2.2 Motor and Commutating Transistors

Figure 4.4. Since the phase windings are separated by sixty mechanical degrees, the flux in each phase is seen to have a sixty degree phase shift with respect to the adjacent phases. The explanation of the shape of the model flux is discussed in Chapter Four. The electronic commutation must be performed in such a manner as to complete two electrical cycles for each mechanical rotation since the flux distribution completes two cycles in one rotor rotation. The commutation of the armature (stator) current is accomplished every thirty degrees of rotor rotation because a new winding "enters" the magnetic field with every thirty degrees of rotation simultaneously with another winding "leaving" the magnetic field. The sensor and switching logic for motor

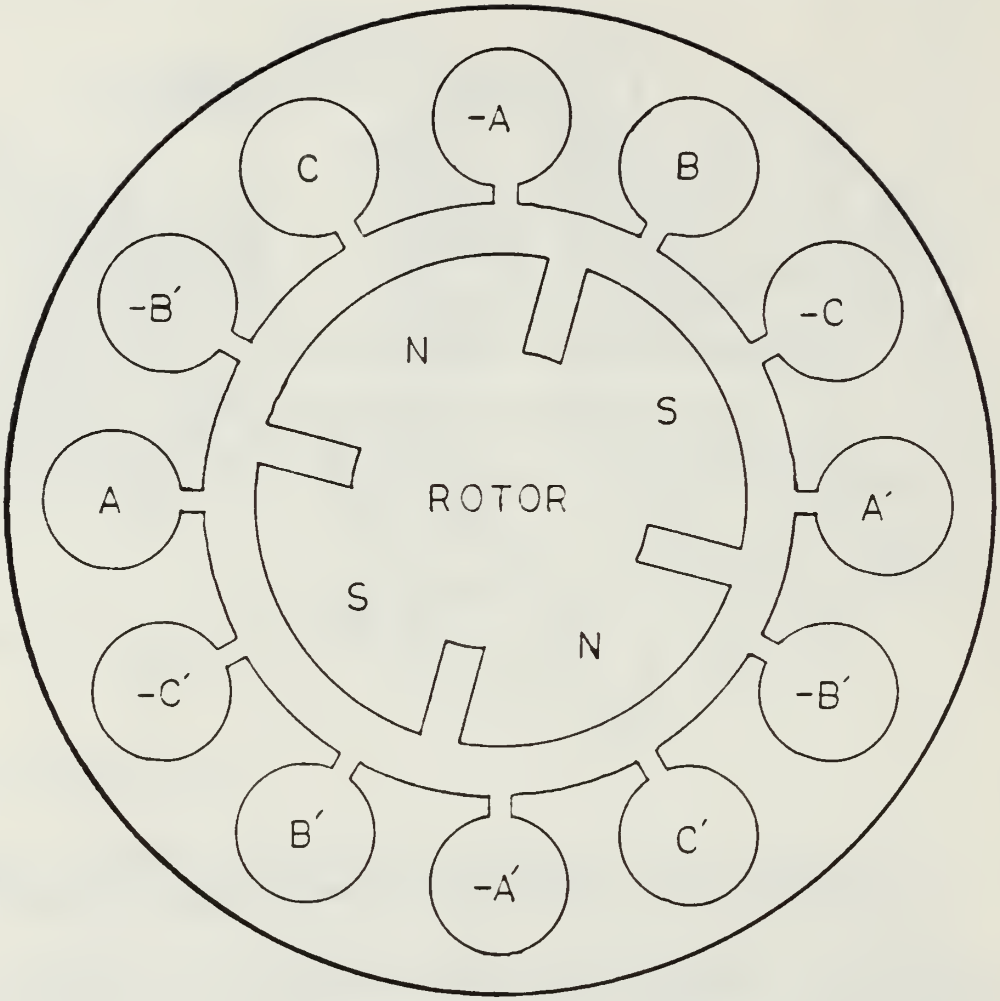


Figure 2.3 Motor Stator and Winding Configuration

rotation is tabulated in Table II, and indicates the sensor logic level (RPS), and connection of the phase terminals for both clockwise and counterclockwise direction for each thirty degrees of rotor position. Note that regardless of direction of rotation, the rotor position logic remains constant for a given rotor position, and that rotor positions between 180 degrees and 360 degrees are indistinguishable from rotor positions between zero and 180 degrees because of the rotor symmetry.

TABLE II

Sensor and Switching Logic

Counterclockwise Rotation

ROTOR POSITION	RPS A	RPS B	RPS C	PHASE A	PHASE B	PHASE C
0	0	1	0	open	neg	pos
30	1	1	0	pos	neg	open
60	1	0	0	pos	open	neg
90	1	0	1	open	pos	neg
120	0	0	1	neg	pos	open
150	0	1	1	neg	open	pos

Clockwise Rotation

ROTOR POSITION	RPS A	RPS B	RPS C	PHASE A	PHASE B	PHASE C
0	0	1	0	open	pos	neg
30	1	1	0	neg	pos	open
60	1	0	0	neg	open	pos
90	1	0	1	open	neg	pos
120	0	0	1	pos	neg	open
150	0	1	1	pos	open	neg

C. MOTOR SYSTEM EQUATIONS

Derivation of the basic motor system equations (equations 2.1 through 2.8) was accomplished by Thomas in [Ref. 1] and they are repeated here for convenience. From Kirchoff's voltage law, the stator voltage must be:

$$Es(t) = LdI/dt + RI(t) + Eb(t) \qquad (2.1)$$

where the back emf voltage can be described by:

$$Eb(t) = (Km\ \Phi)\,Wm(t) = KbWm(t) \qquad (2.2)$$

$$\text{or}\quad Eb(t) = Kbd\theta m(t)/dt$$

$$\text{since}\quad d\theta m(t)/dt = Wm(t).$$

Rearranging Equation 2.1 for the highest derivative on the left side yields:

$$dI/dt = (1/L)Es(t)-(R/L)I(t)-(1/L)KbWm(t). \tag{2.3}$$

The mechanical torque balance equation is:

$$Tm(t) = JdWm(t)/dt + BWm(t) + Tl(t). \tag{2.4}$$

Rearranging yields:

$$dWm(t)/dt = (1/J)Tm(t) - (1/J)Tl(t) - (B/J)Wm(t) \tag{2.5}$$

The total viscous friction (B) and total load inertia (J) is represented as follows:

$$B = Bm + Bl \tag{2.6}$$

$$J = Jm + Jl \tag{2.7}$$

where Bl = Blp/N and Jl = Jlp/N. Blp is the viscous friction associated with the load, Jlp is the load inertia and N is the gear reduction ratio. The link between the electrical and mechanical equations is the torque constant, which is derived from the magnetic flux:

$$Tm(t) = Km\Phi I(t) = KtI(t). \tag{2.8}$$

The basic equations have been enhanced in this model to take advantage of inherent sign conventions, particularly in direction of current flow. This in turn makes the commutation procedure more apparent in the generated graphics. For example, the primary motor currents are depicted in Figure 2.2, each having an assigned positive direction as pictured. The difference between IAB and ICA yields IA, IBC minus IAB equals IB and ICA minus IBC equals IC. The current flow cannot always be positive as depicted, since the sum of the three phase currents must be identically zero by Kirchoff's current law. Therefore, at least one of the currents IA, IB or IC must be negative at any given time, representing a flow of current returning to the power supply. From the current waveform it is immediately apparent which phase is connected to the negative supply and which is connected to the positive supply simply by observing the polarity of the current (see Figure 5.2). The concept of the positive and negative supply voltages is totally equivalent to a single positive (or negative) supply as used in [Ref. 1] and since the drive currents are calculated from the difference of two fictitious currents, a single supply will work in the simulation, but the split supply enhances the symmetry of the motor currents and voltages. This change allows for improved modeling and conceptualization of transient studies as discussed in the next section.

D. MODEL DEVELOPMENT

The basic simulation of the brushless DC motor by Thomas used a single positive or negative power supply and superimposed armature leg currents to produce the measured motor performance. Motor drive was then realized by multiplying averaged armature currents by a torque factor for the model under development. In the this model the supply is a split supply of equal voltages. Armature current is assigned a positive sign if it flows in the positive direction (i.e. into the motor) as shown in Figure 2.2 and a negative sign if it flows in the opposite direction (i.e. out of the motor) as discussed previously. A secondary result of the model of commutating transistors and split supply is that motor reversal cannot be accomplished by reversing the polarity of the power supply as in [Ref. 1] but must instead be accomplished as in a typical power conditioner by proper reverse sequencing of the commutation, shown in Table II, and discussed in Chapter 5.

Several models were produced whereby each model represented a completion of a particular aspect of the system such as motor air gap flux and power conditioner transistor switching characteristics. The early models were developed from simple ideas such as instantaneously switching, zero or infinite resistance transistor switches and constant air gap flux. Each model improved a particular area under development until it was thought to be a suitable representation of an actual motor or power conditioner feature.

The first model incorporates a square wave of back emf (constant flux) and endeavors to demonstrate transistor commutation effects. The transistor switching is instantaneous and is accomplished within the "commutation and Hall effect" procedure (see Appendix C).

The second model introduces changes in the transistor switching. While switching is still instantaneous, typical values of transistor saturation and cutoff resistance are introduced, and commutation is controlled by the commutation procedure instead of being accomplished by that procedure. This feature leads to the next model which simulates the actual rise time and saturation delay of power transistor switching. This model is the basis for all subsequent simulations involving increased model complexities such as the sinusoidal flux model.

The remaining simulations develop the voltage and current relationships between the motor and electronic commutator final drive transistors and incorporate sinusoidal magnetic flux models consisting of a fundamental and fifth harmonic as described in Chapter Four. These program listings are contained in Appendix B. The first of these models continues to simulate the transistors without the protecting diodes (which are shown in Figure 2.2) in order to demonstrate the inductive voltage transients produced by opening one of the stator winding circuits with a transistor switch. The next model adds the damper diodes to the power conditioner to fully simulate the power conditioner final drive elements. The final model takes all the complications of the preceeding ones and depicts the transient behavior of the system during reversal ("plugging") of the rotating motor. The results of computer runs using this model are discussed in Chapter Five. No attempt has been made to reduce the order of the model in these simulations since the desire was to observe both the fast and slow time constant effects. The numerical integration of the differential equations of such a "stiff" system to evaluate the steady state behavior can be somewhat time consuming. Transistor time constants are user adjustable as are saturation and cutoff parameters. The motor parameters used for the model development are typical for the brushless motors now available for this type of application, but are not representative of any particular motor. As such, all motor parameters are user adjustable to conform to any desired motor performance that would meet design objectives.

III. ELECTRONIC COMMUTATION

A. THREE PHASE BRIDGE CIRCUITRY

The three-phase, four pole brushless DC motor is depicted in Figure 2.2. The transistor and diode configuration is very similar in appearance to a three phase full wave bridge rectifier circuit and acts in a very similar fashion. The composite flux shown in Figure 4.6 is a demonstration of this similarity. The composite flux actually corresponds to the peaks of the back emf voltage waveform in Figure 4.5 as if it were rectified in a three phase full wave bridge rectifier. This figure was generated by taking the normalized flux model for the two conducting phases during each commutation interval, adding them together, multiplying by the torque coefficient and converting to webers (the torque coefficient has the same basic units of force-length/amp). Actually, the diodes may be used as a full wave bridge rectifier for some applications (e.g. to recharge batteries) when the motor is driven by the load torque and acts as a generator [Ref. 3].

Transistors Q1 through Q6 control the current switching in accordance with the timing diagram in Figure 3.1, where a logical "1" corresponds to the transistor being in the conduction mode. This diagram was derived for counterclockwise rotation (positive direction) as the current will be positive in each winding as the north pole of the rotor is positioned in its field (positive flux) and the current will be negative when the south pole of the rotor is positioned in its field (negative flux). A similar timing diagram can be made by considering the logic for clockwise rotation (negative direction) in Table II.

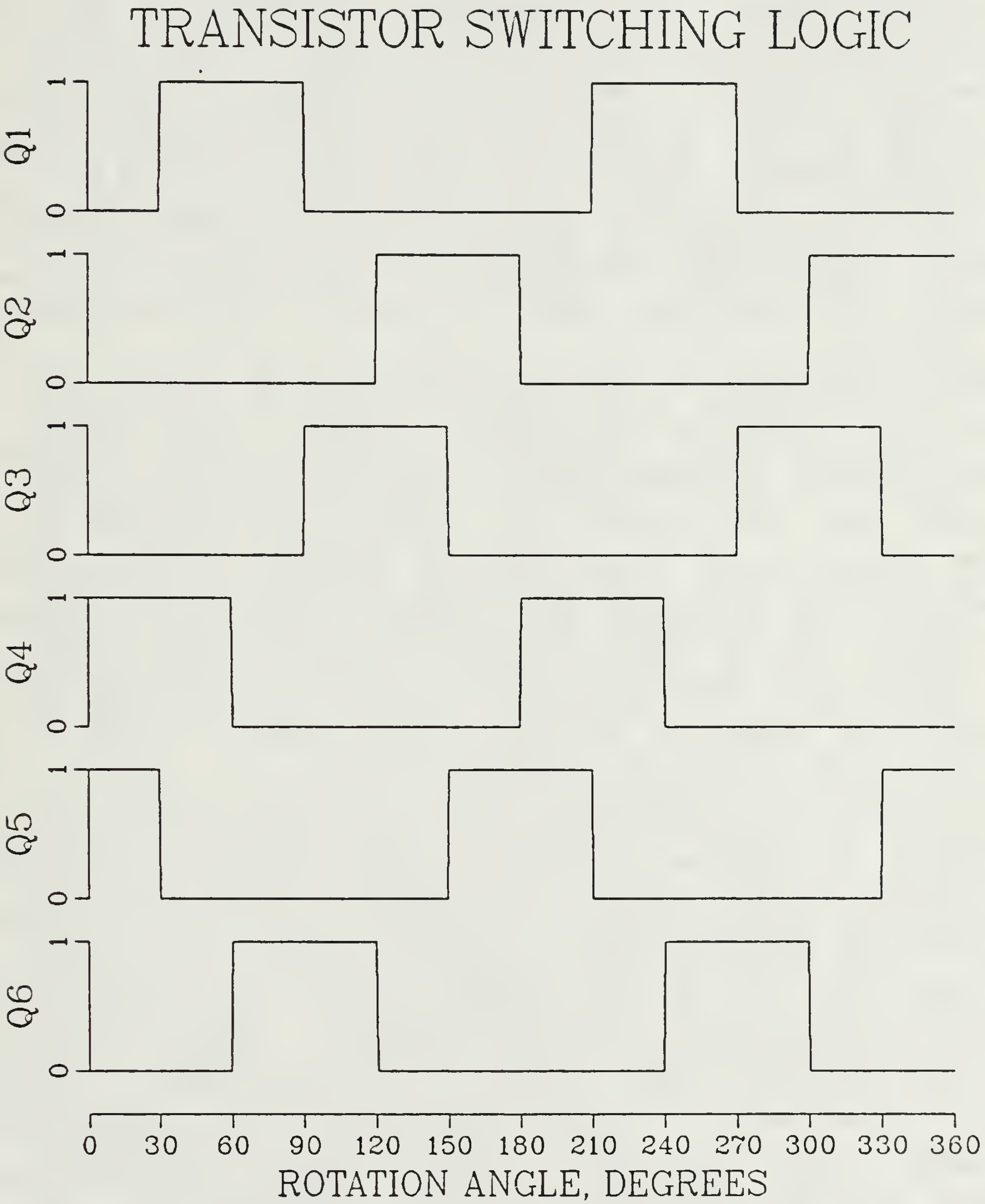


Figure 3.1 Transistor Timing Diagram
(Level 1 Represents "On")

B. SWITCHING TRANSISTOR DYNAMICS

Behavior of transistors in the cutoff and saturation regions differs somewhat from the more typically understood small signal models. Some discussion of switching characteristics and the resulting model is in order. This discussion assumes a generic transistor and is equally correct for PNP and NPN devices, as the discussion describes primarily base region effects. It might be necessary to keep in mind that electrons are majority carriers for n-type base regions and holes are majority carriers for p-type regions. This discussion of transistor behavior follows that found in [Ref. 4].

When a transistor is operating in the cutoff region, the emitter and collector are reverse biased, base region minority carrier concentration is practically zero at the junctions, and each junction is drawing some fraction of leakage current Ico. The majority carriers which are collected at the junctions are thermally generated in the base region, and a (small) minority carrier current will flow out of the base terminal to keep the base region neutral. The amount of minority carrier charge stored in the base region is negligibly small.

To turn the transistor on, charge carriers must be injected at the emitter junction so that there will be a large charge gradient toward the collector. This means that there must be minority carriers stored in the base region and there must be a corresponding change in majority carriers to neutralize the stored charge. Thus current flows into the base region through the base terminal as the storage takes place. If the base current is suddenly increased, there will be a large charge distribution gradient near the emitter and a small gradient near the collector, the difference in slope being proportional to the base current. Eventually the charge distribution will become more uniform with a constant gradient of charge between the emitter and collector. This is the normal active transistor region. If the load line of the circuit is such that the transistor is allowed to pass through the active region and enter the saturation region, the collector current reaches a maximum value and cannot increase. The collector to base voltage is then very small, but the base current can be increased further so that the minority carrier distribution in the base region has essentially zero gradient from the emitter to collector. This creates a large excess of minority carriers at the collector junction which in turn causes the collector to be forward biased. This is a state in which there is more charge at the collector than the collector can collect. In this condition, the collector to emitter voltage is smaller than either of the junction voltages.

The amount of charge stored in the base region in this condition is very large. Additionally, since the collector junction is forward biased, excess minority carriers will cross the junction from the base region and, if the minority carrier lifetime is sufficiently long, be stored in the collector region as well as in the base region. This stored minority-carrier charge has a deleterious effect on the turn-off time of the transistor. In order to turn off the transistor, the minority carrier density at the collector junction must be reduced to zero for the collector voltage to start to recover. When turn-off begins, the charge gradient is smaller at the emitter than at the collector, resulting in current flow into the base lead and minority carriers disappearing from the base region.

The collector current remains unchanged until the storage period is over and collector voltage remains small. As the transistor enters the active region, the remaining charge is swept out of the collector and emitter. The minority carrier density at the collector is again small, and the charge gradient is decreasing rapidly. As soon as minority carrier density reaches zero at the emitter, it may also become reverse biased. This turn-off process is one of the important limitations on the switching response of transistors.

The turn-on time for a simple switch is approximated by the following equations: [Ref. 4]

CC: $$I_E = \frac{I_{B,on}}{1-\alpha_B}\left(1 - \exp\frac{-t}{T_{cc}}\right) \qquad (3.1)$$

$$T_{cc} = \frac{1}{\omega_\alpha\,(1-\alpha_B)} \qquad (3.2)$$

CE: $$I_c = \alpha_E\, I_{B,on}\,\Bigl(1 - \exp\frac{-t}{T_{cE}} \qquad (3.3)$$

$$T_{cE} = \frac{1}{\omega_\alpha\,(1-\alpha_B)} \qquad (3.4)$$

where $$\alpha_B = -\frac{I_c}{I_E} \qquad (3.5)$$

and $$\alpha_E = \frac{I_c}{I_E} \qquad (3.6)$$

and ω_α is the -3dB alpha cutoff frequency.

The effects of overdrive and reverse drive on transistor switching performance are demonstrated in Figure 3.2. If not overdriven, it takes approximately three time constants (Tcc or Tce) to reach saturation. A significant improvement in rise time is realizeable by the use of base overdrive. If a transistor is overdriven, its effective gain is decreased, but this has the effect of slightly reducing the time constant while, more significantly, attempting to drive the transistor to higher steady state current--resulting in a greater initial slope. The combination of the two effects results in rise times on the order of .7 time constants to reach saturation.

The turn-off time for a simple switch is characterized by the following equations: [Ref. 4]

CC: $$I_E = I_E^- \exp\frac{-t}{T_{cc}} - \frac{I_{B,off}}{1-\alpha_B}\left(1-\exp\frac{-t}{T_{cc}}\right) \qquad (3.7)$$

CE: $$I_C = I_C^- \exp\frac{-t}{T_{CE}} - \alpha_E I_{B,off}\left(1-\exp\frac{-t}{T_{CE}}\right) \qquad (3.8)$$

and I_E^- and I_C^- are currents just prior to turn-off, and I_B,off is the base drive current immediately following turn-off initiation. An inspection of equations 3.7 and 3.8 reveals that the turn-off time is affected by two mechanisms, one of base drive current and one of collector or emitter current initial condition. Reducing the initial condition of collector or emitter current or increasing the base drive current results in a proportional decrease in turn-off time.

One of the difficulties of overdrive is storage time which is a function of the excess base current. Storage time for a simple switch is described by equations 3.9 and 3.10:

CC: $$T_s = T_{so} \ln \frac{I_B^+ - I_B^-}{I_B^+ - I_E(1-\alpha_B)} \qquad (3.9)$$

CE: $$T_s = T_{so} \ln \frac{\alpha_E (I_B^- - I_B^+)}{I_C^- - \alpha_E I_B^+} \qquad (3.10)$$

where $$T_{so} = \frac{\omega_\alpha + \omega_\alpha'}{\omega_\alpha \omega_\alpha' (1-\alpha_B \alpha_R)} \qquad (3.11)$$

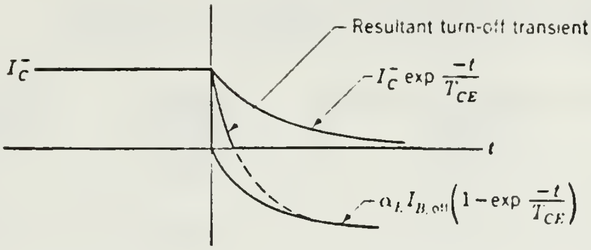
and α_R corresponds to α_B with collector and emitter terminals reversed, and ω_α' is the -3dB alpha cutoff frequency with collector and emitter terminals reversed. [Ref. 4 and 5].

It is most desirable to minimize the storage time and this can be accomplished by overdriving during turn-on, reducing the base drive to hold the transistor near saturation and finally drive it off quickly using reverse drive. This can be accomplished neatly and simply by bypassing the base resistor with a suitably sized capacitor as discussed in [Ref. 6 :p. 784].

C. MODEL OF SWITCHING TRANSISTOR DYNAMICS

The preceding discussion leads into the modeling of the transistor switches as dynamic elements. The most desirable transistor model would be of low order and not add significantly to the program complexity since the motor dynamics are the prime concern.

The initial models were developed with the transistor switches acting instantaneously between cutoff resistance and saturation resistance. This was satisfactory as long as the transients generated remained small. Using the variable step size integration routines available with CSMP, it was found that the rapid switching drove the integration step size minutely small and computer time for the simulation to reach steady state became excessively long. Based upon the discussion given in the preceeding section on transistor switching, an exponential rise and fall was developed, and both overdrive and reverse drive simulated by clipping the exponential rise and decay within limits of the saturation resistance and cutoff resistance. This not only provided a good simulation of the transistor switching with user variable parameters, but also eased the computer time problem somewhat. The resulting switching characteristics are shown in Figure 3.3, (with exaggerated time constants for clarity) and compare favorably with those shown in Figure 3.2 (a) and (b). Figure 2.2 suggests that the transistors are bipolar NPN devices. This was done for pictorial reference only.


Resultant turn-off transient
I_C^-
$-I_C^- \exp \frac{-t}{T_{CE}}$
t
$-\alpha_L I_{B,\text{off}}\left(1-\exp\frac{-t}{T_{CE}}\right)$

The improvement in turnoff time which is possible by reverse drive is shown here.

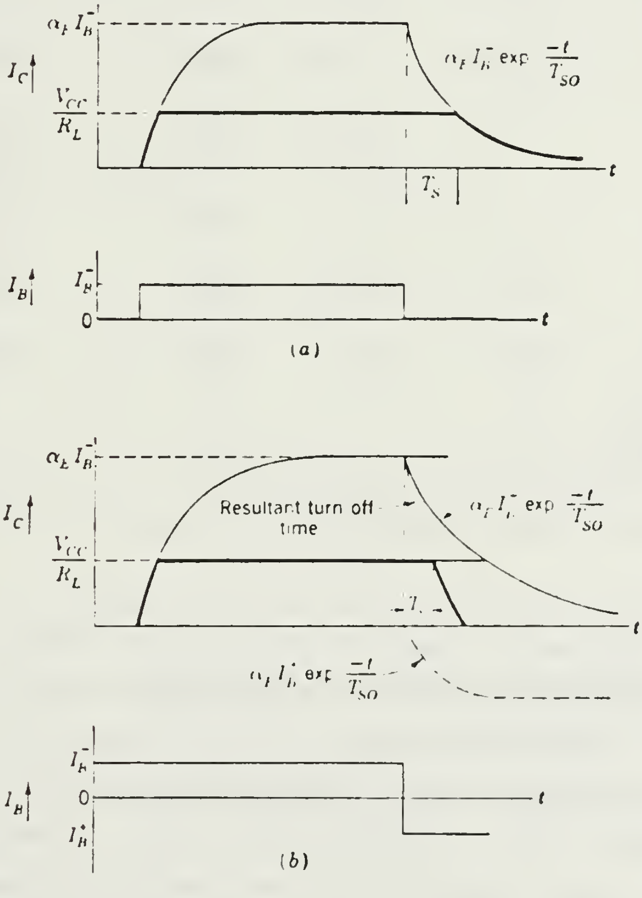


Figure 3.2 Switching Characteristics. (a) Overdrive only. (b) Overdrive and Reverse Drive.

TABLE III

Some Power Transistor Specifications

Device	Ic(Max) Amps	R(sat) Ohms	ts s	Diss Watts	Vbr(sus) Volts
MTM45N15 (MOS)	45*	.06%		250	150
MTM40N18 (MOS)	40*	.08%		250	180
MJ16016 (Bipolar)	20		2.2	250	450
MJ15011 (Bipolar)	10			200	250
2N3430 (Bipolar)	5	.2	4.0	150	100
2N2777 (Bipolar)	30	.06	14**	200	150
2N6250 (Bipolar)	15		3.5	175	275
2N6339 (Bipolar)	25		1.0	200	120
2N1820 (Bipolar)	15	.1	25**	250	250
STC2231 (Bipolar)	30	.08	6#	200	200

*ID **ts+tf
%R(on) #td+tr

These switching transistors may be a pair of complementary symmetry Class B amplifier output devices to take advantage of emitter-follower characteristics or might be MOS devices to realize high transistor power efficiency. The model as presented is accurate for bipolar transistor dynamics but because switching time constant and on and off resistance are the only parameters for the model, it should be extendable to include MOS devices as well. The parameters used for the simulation program were a switching time constant of

1.5 microseconds and a saturation resistance of .05 ohms. These values were chosen as more or less ideal values, the combination of which would probably not be realized in any one device. In Table III some transistor specifications are listed for devices which might be desirable to use for this motor controller application. The fast switching times for the bipolar transistors are their salient feature, while the low "on" resistance of the MOS devices makes them desirable.

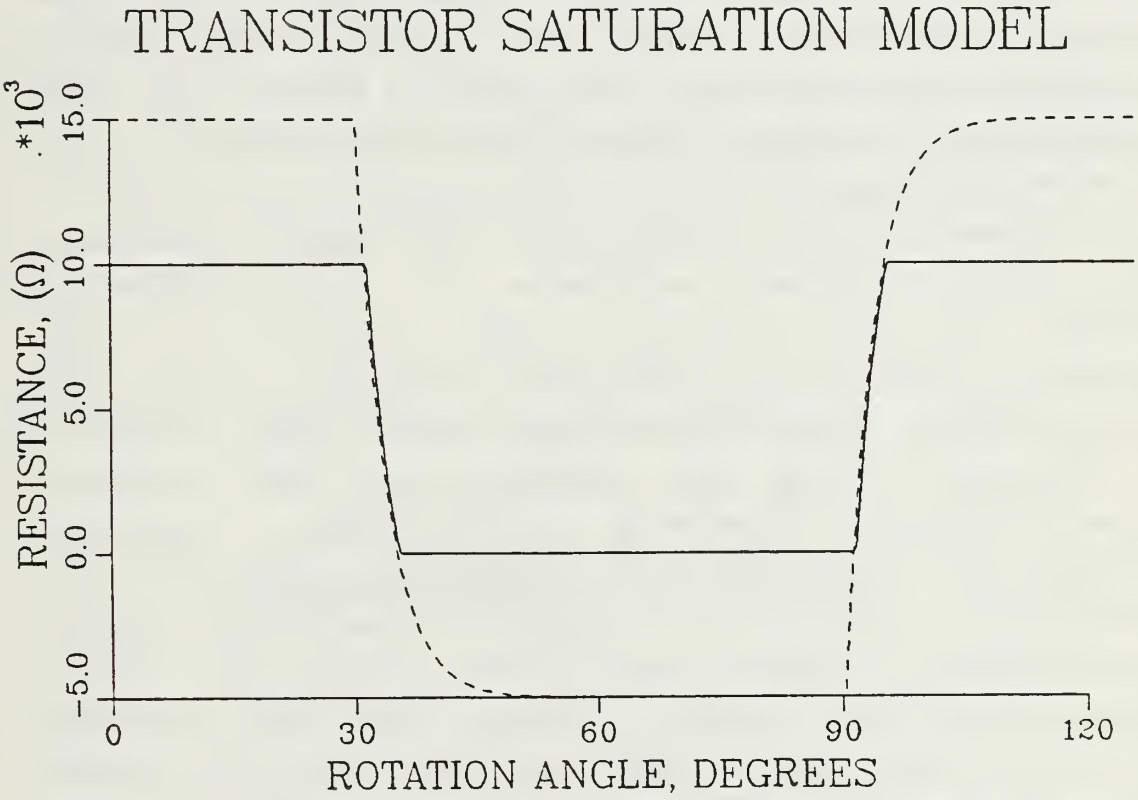


Figure 3.3 Transistor Model Saturation Characteristics

The model developed to this stage has ignored the effect of peak reverse voltage across the transistors that occurs at the moment of commutation due to the opening of the inductive circuit. To provide the required protection, damper diodes are used to clamp the spike voltage to the positive or negative supply. The diodes not only provide overvoltage protection for the transistors, but must handle nearly the full value of steady state current for a brief period of time as well. The effect of the diode clamping can be seen immediately by comparing the figures depicting motor current with and without the diodes in the simulation. (See Figures 5.1 and 5.2) Note that the current dip is markedly reduced when the diode is in the circuit. The diodes provide a commutation of the transistor current and maintain current flow in the motor during the switching of the drive current between two phases. Additional information concerning diode commutation was found in [Ref. 9 :p. 371] concerning the so-called "Jones" commutation circuit for a DC motor controller.

The diode model is very simple and features instantaneous switching between saturation and cutoff resistance identical in value to that of the transistors. This approach did not add any appreciable complexity to the integration problem because the diodes pick up the current as the transistor turns off, smoothing out the transient current instead of generating another current transient. The switch of the current to the diode is triggered by the voltage spike caused by the transistor turning off, similar to what would be expected in the actual circuit. The lack of a diode voltage drop before the knee of the diode conduction curve is the only addition that might be made to the model, but was deemed unnecessary as the voltage drop across the diode at full motor current would still be less than one volt and of the same order of magnitude.

IV. MAGNETIC FLUX MODEL

A. SYMMETRIC FIFTH HARMONIC FLUX

Thomas [Ref. 1] derived a combination fundamental and fifth harmonic reverse voltage waveform from empirical measurements. This model has been used in this thesis with modifications. The phase relationship of the fifth harmonic to the fundamental has been altered to provide the same shape voltage waveform across two windings instead of across only one. This agrees with the empirical data and also gives rise to a new magnetic flux model, the shape of which agrees in form with traditional DC machines [Ref. 8]. The general shape of the flux-density distribution of a DC motor is shown in Figure 4.1.

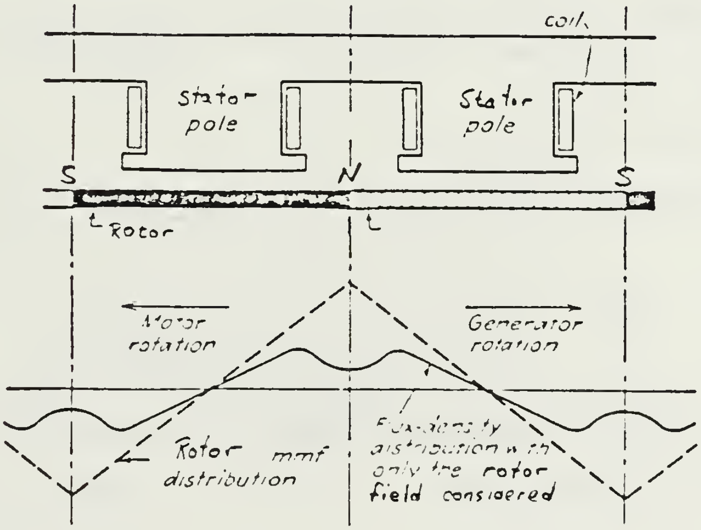


Figure 4.1 Flux Density Distribution due to Rotor Field

The dip in the center of the flux-density distribution can best be explained by considering Figures 4.2 and 4.3 which are flux maps of the magnetic field due to the rotor magnets and stator current respectively and confirm the distribution shown in Figure 4.1 for either stator or rotor considered. In Figure 4.2 and Figure 4.3, separation of flux lines indicates degree of field strength, with greater separation indicating less field strength.

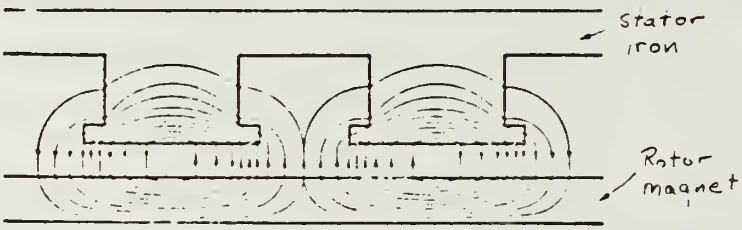


Figure 4.2 Flux Map with only Rotor Field Considered

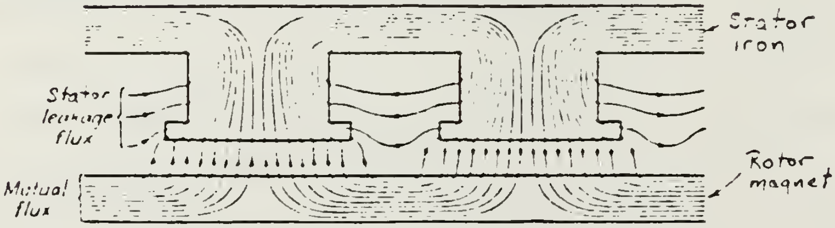


Figure 4.3 Flux Map with only Stator Field Considered

The model flux-density distribution is depicted in Figure 4.4 showing the phase relationship between the three windings. In Figure 4.5 the phase 'A' flux is shown along with the resulting generated voltage between terminals 'A' and 'B'. The dotted lines in each figure represent the commutation periods during which each winding is connected to the positive supply, the negative supply, or effectively disconnected from supply by the switching power transistors. The commutation effects shown by the dotted lines in these figures represent motor currents for counterclockwise (positive) rotation as the product of the flux and the motor current is seen to always be positive. Since the motor torque is derived from the product of the magnetic flux density distributions and the current flowing in each phase winding, this results in a positive motor torque and rotation in the positive direction. The composite flux density distribution for the rotating motor is displayed in Figure 4.6, and is used to derive the normalizing constant for the flux density by maintaining the average value for the torque coefficient at the constant value for the simple models. This composite flux density distribution is seen to have an average value equal to the torque constant of the simple models, when the conversion from webers to inch-ounces per amp is applied:

$$(\text{in-oz/amp}) \times (.00707) = \text{webers} \qquad (4.1)$$

This figure also provides a quick check on the back emf constant since the numerical value of both constants must be identical in MKS units.

To demonstrate clockwise rotation, the flux model remains fixed with respect to the shaft position, but the sign of the currents must be reversed. This amounts to reversing the polarity of the commutation scheme for a

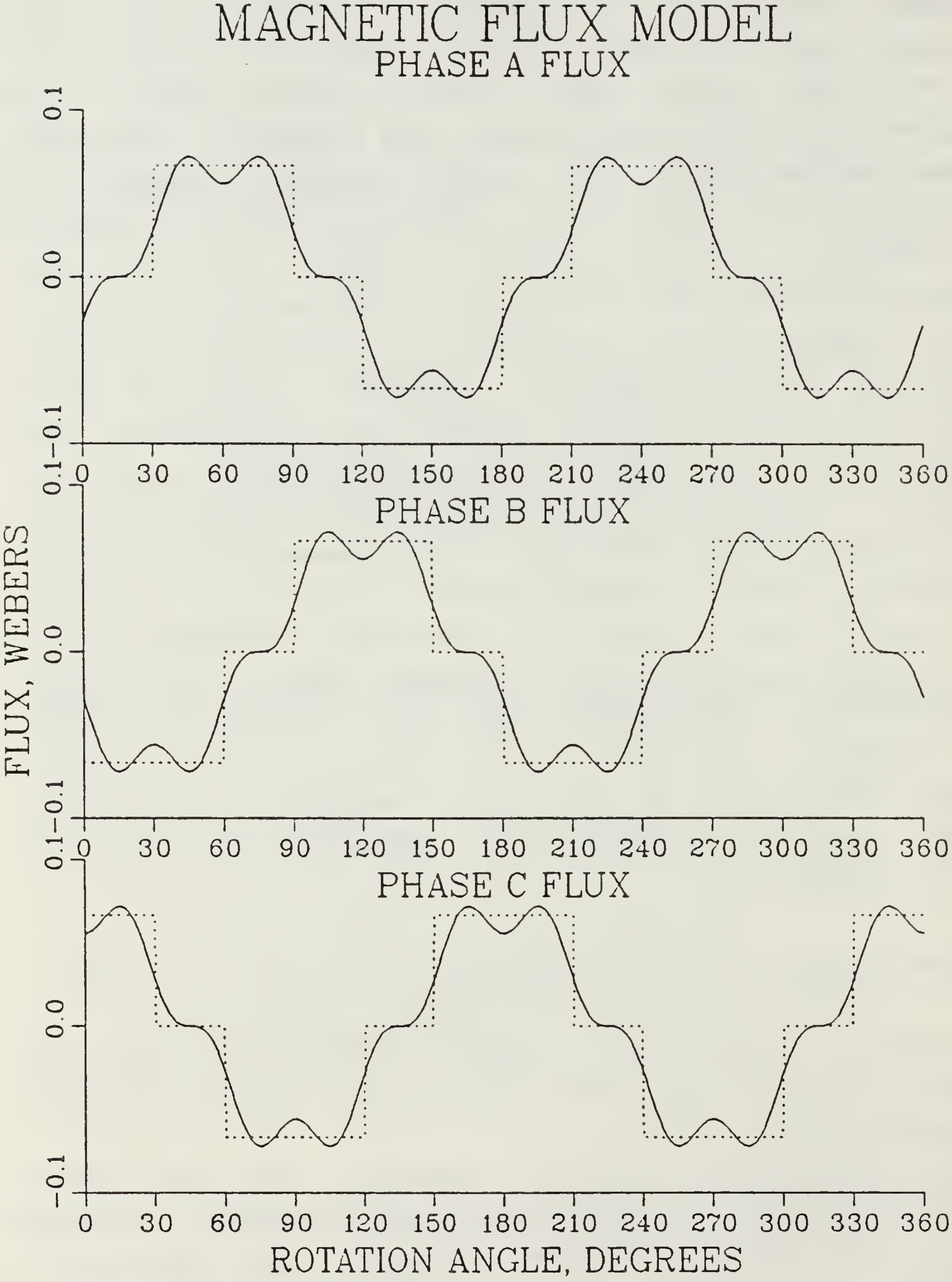


Figure 4.4 Model Flux--Phase Relationship

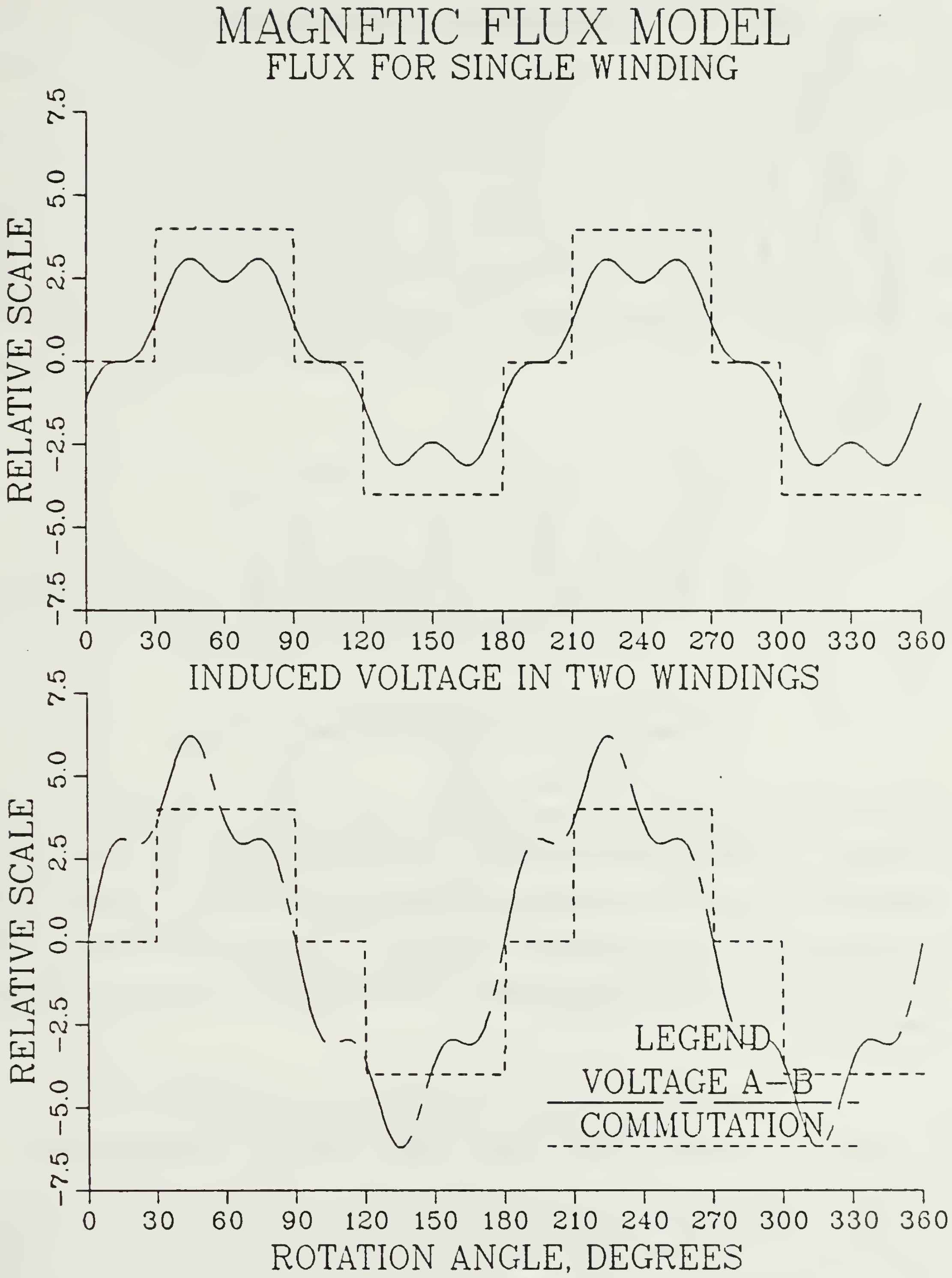


Figure 4.5 Model Flux and Back EMF Voltage

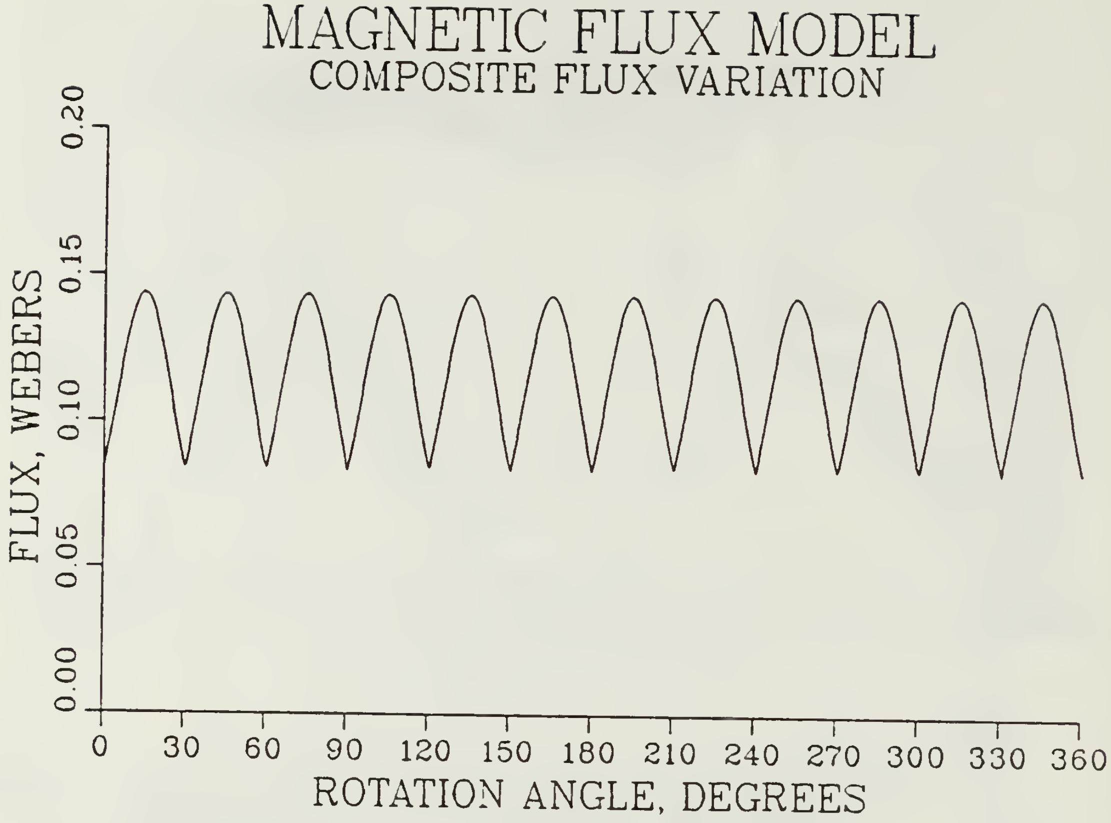


Figure 4.6 Model Composite Flux

counterclockwise rotating motor. As can be seen from Table II this is the same sequence of commutation as for counterclockwise rotation advanced by ninety degrees, which should be expected from the rotor geometry since the south pole of the rotor is displaced ninety degrees from the north pole of the rotor.

B. FIFTH HARMONIC FLUX WITH DRIVE CURRENT INTERACTION

The interaction of the two magnetic fields, one due to the rotor magnets and the other due to the stator current causes distortion of the air gap flux and hence the generated voltage waveform. Reference eight indicates that such an interaction is expected, but as to what degree the flux density distribution and the reverse voltage waveform would be distorted is unknown. The expected effect of the two magnetic fields interacting is to skew the symmetrical distribution as is shown in Figure 4.7 It is realized that the profile of the flux model of Figure 4.5 and the total flux density distribution as shown in Figure 4.7 do not agree, however the flux model shows a high degree of correlation to empirically measured experimental test data for this type of motor [Ref. 11].

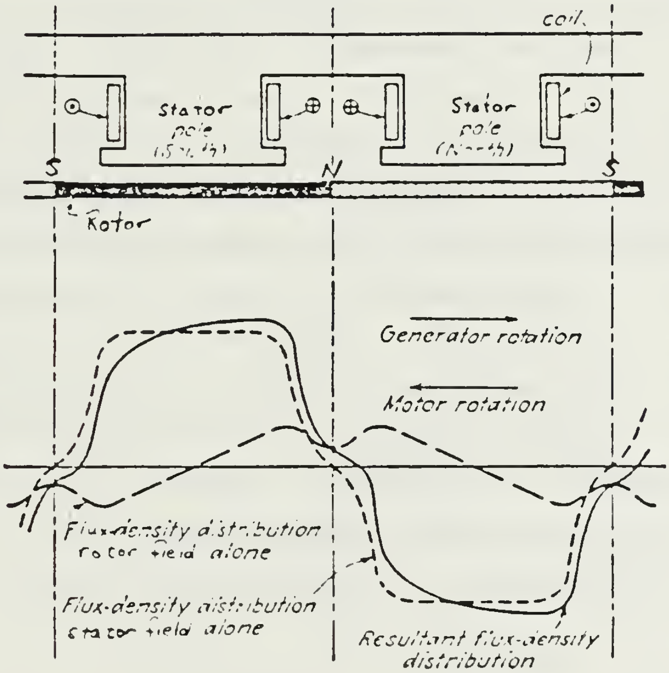

coil
Stator pole (South)
Stator pole (North)
S
N
S
Rotor
Generator rotation
Motor rotation
Flux-density distribution rotor field alone
Flux-density distribution stator field alone
Resultant flux-density distribution

Figure 4.7 Flux Density Distribution Demonstrating Interaction.

The skewed shape of the resultant flux-density distribution due to stator current interaction can be simulated by slipping the phase relationship of the fifth harmonic with respect to the fundamental. If the phase shift is simply a constant, then two windings will produce essentially the same shape of back EMF voltage as the previous model, but combination with the other winding will not be similar or symmetric. Since current, as modeled, essentially flows in two windings at a time, the distortion must be a function of the current and the third winding flux must remain undistorted as long as that winding has no current flowing. This thinking led to the model for interactive flux depicted in Figure 4.8. The phase relationship between fundamental and harmonic is identical to the non-interactive model if the drive current is zero. In the presence of drive current, the fifth harmonic is shifted smoothly and continuously until at maximum current, the phase shift is thirty electrical degrees. Even with this visible warping of the flux, the back emf voltage waveform is recognizeable as a fundamental and a fifth harmonic, and this effect might be smaller than depicted, and of little consequence to the motor designer. Additionally, no model of magnetic saturation has been implemented, which would have the effect of flattening the flux peaks and giving a more constant maximum flux and hence torque, resulting in smoother motoring. Such effects are expected in an actual motor, but at what value of current the saturation should begin will have to be determined by measurement of a particular motor.

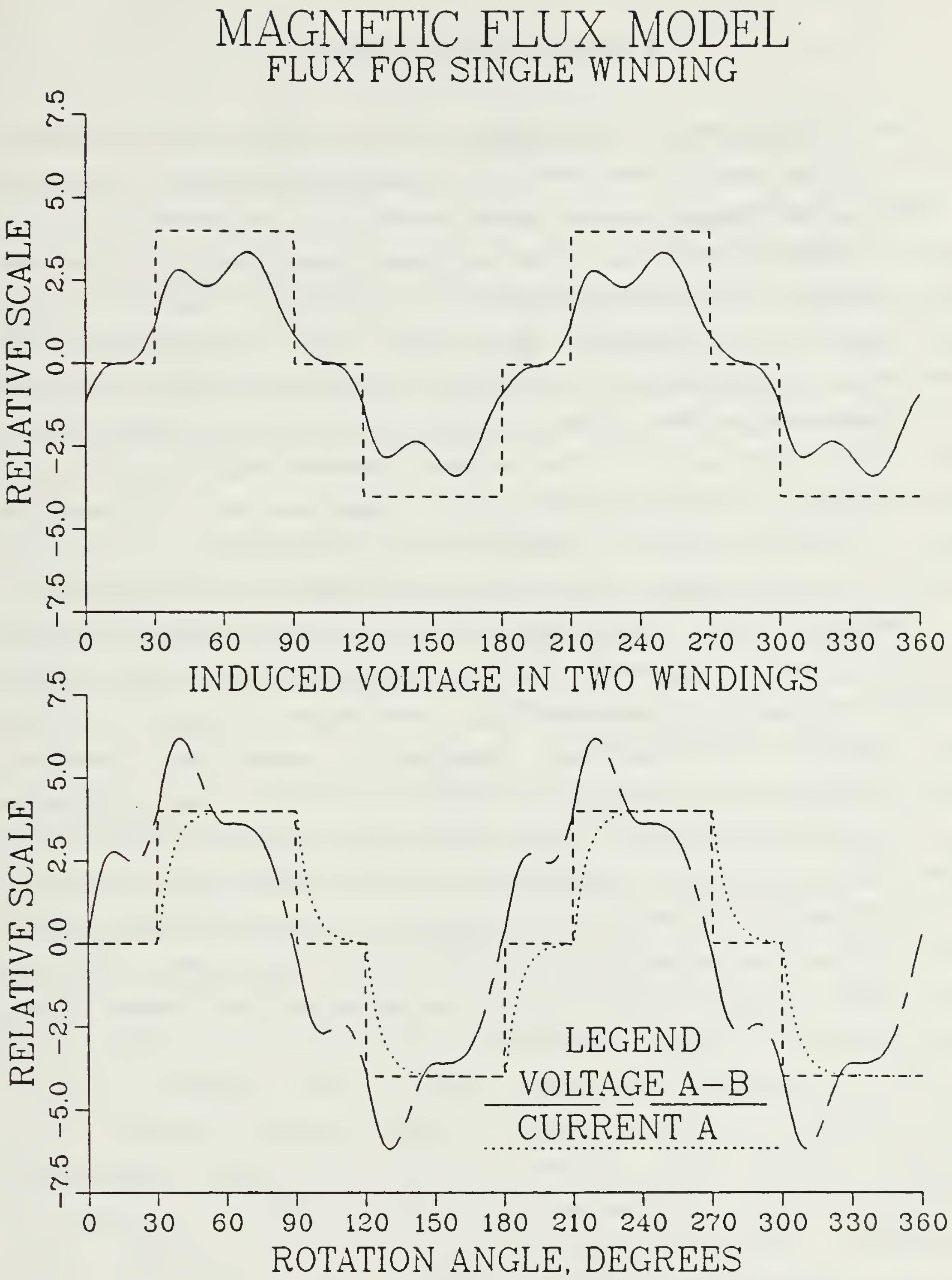


Figure 4.8 Model Flux and Back EMF Voltage Demonstrating Drive Current Interaction

V. MODEL PERFORMANCE

The performance of the first three models is not interesting to the motor designer as the simplifications involved in these simulations reduce the resulting behavior to textbook DC motor dynamics. As a development tool for other simulations, the structure may be of some interest. These simulations are included in Appendix C for this reason. The transistor switching of the fourth and all subsequent models is of interest in that the transistor impedance affects the (L/R) time constants of the motor current and is an important feature in understanding the behavior of the simulations. Because of the varying time constants, decay of current in one phase and buildup of current in another phase at commutation is not compensatory. The current decays faster in the turn-off winding than the corresponding buildup in the turn-on winding, while the current in the third winding is ostensibly constant. The third winding current cannot be constant because all three currents must sum to identically zero. The result is the sharp dip in the center of the current waveform of the unswitched winding. Excellent correlation of this effect is seen in the experimental data as shown in Figure (12) of [Ref. 10] and [Ref. 11]. In simulations which include a diode model, the dynamic equations that determine the (L/R) time constant are expanded to include the diode model. The inclusion of the diode impedance in the dynamic time constant results in a "bracing up" of the current waveform of the unswitched winding yeilding a higher average motor current. This can be observed by comparing Figures 5.1 and 5.2. Models with simulated diodes demonstrate somewhat more torque and speed with slightly less speed ripple than those without diodes.

The final versions, in which the transistor and diode models and sinusoidal back emf voltage are incorporated are used to characterize an actual motor and power conditioner. The performance curves provided by Thomas [Ref. 1] were used for comparison. As a result, all simulations presented here used a net supply voltage of thirty volts, or plus and minus fifteen volts applied to the transistors. As stated earlier the object of this thesis was to provide a tool to evaluate motor and switching transistor performance for various design parameter values and operating conditions. Some deviation from these performance curves was anticipated, but overall characteristics of the torque, current, and power vs speed curves remain of the same form.

At the time of this writing, provisions are being made to gather more comprehensive test data from a typical motor. It is well understood that only a limited number of the model waveforms may be confirmed by measurement. The brushless DC motor is a three wire device, and the voltage across any two windings may be conveniently measured. The simulation, however, calculates and graphs not only the voltage across each pair of windings but in addition, the voltage across each single winding. The individual currents IA, IB, and IC may also be measured with, for example, an inductive coupler or by measuring the voltage drop across a resistor. These measured curves can be readily compared with model results and model parameters adjusted to bring about good agreement.

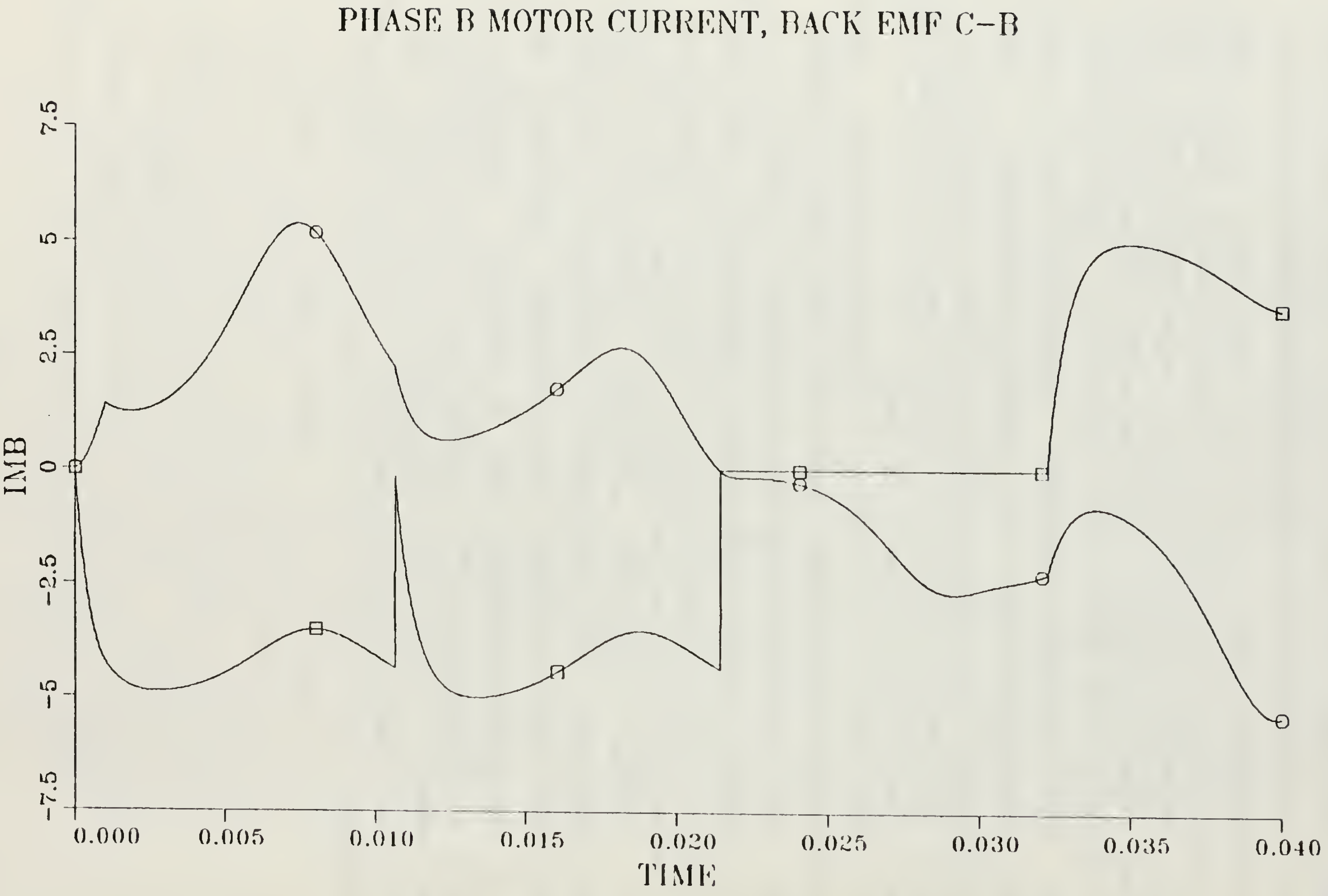


Figure 5.1 Motor Current without Diode Commutation

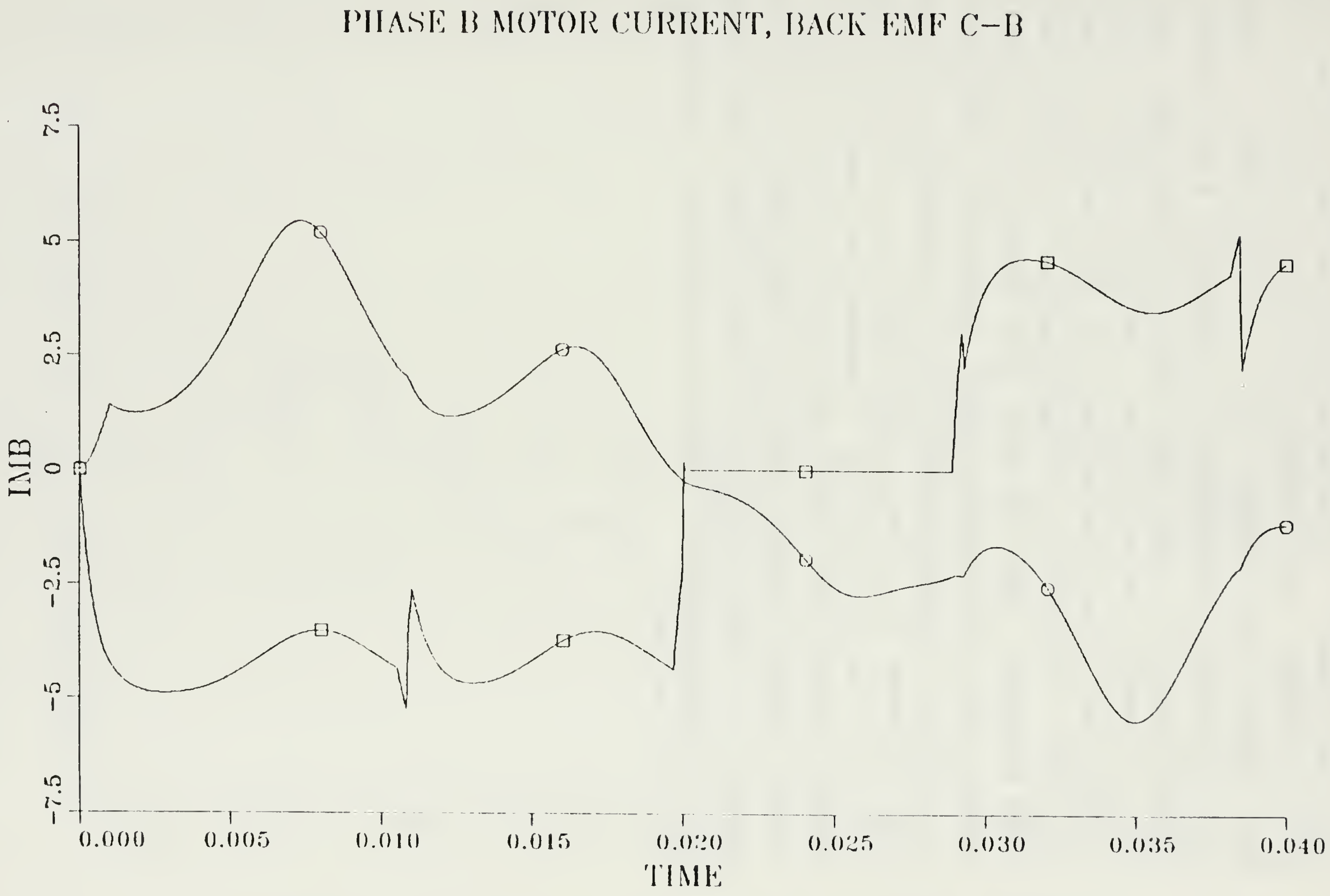


Figure 5.2 Motor Current with Diode Ccmmutation

Motor reversal at speed can be simulated under varying load conditions. In the simulation the load torque opposes motor rotation, and so helps the motor to slow to a stop, then opposes the reversal. If a viscous load was simulated (as in driving a dynamometer), slowing to a stop would take longer because the load would decrease with speed, and the rise to steady state in the reverse direction would be quicker due to the reduced load at low speed. In general, this type of reversal is characterized by large transient motor currents since the back emf voltage is initially of polarity that aids current flow instead of inhibiting it. The reverse torque generated by this current will quickly slow the motor to a stop where there is no back emf generated, and as the rotation reverses the generated voltage changes polarity and once again opposes current flow. The reversal effects can be seen in the current waveforms of Figures 5.3, 5.4, 5.5 and 5.6 which depict motor reversal (from counterclockwise rotation to clockwise rotation) at time = .02 seconds.

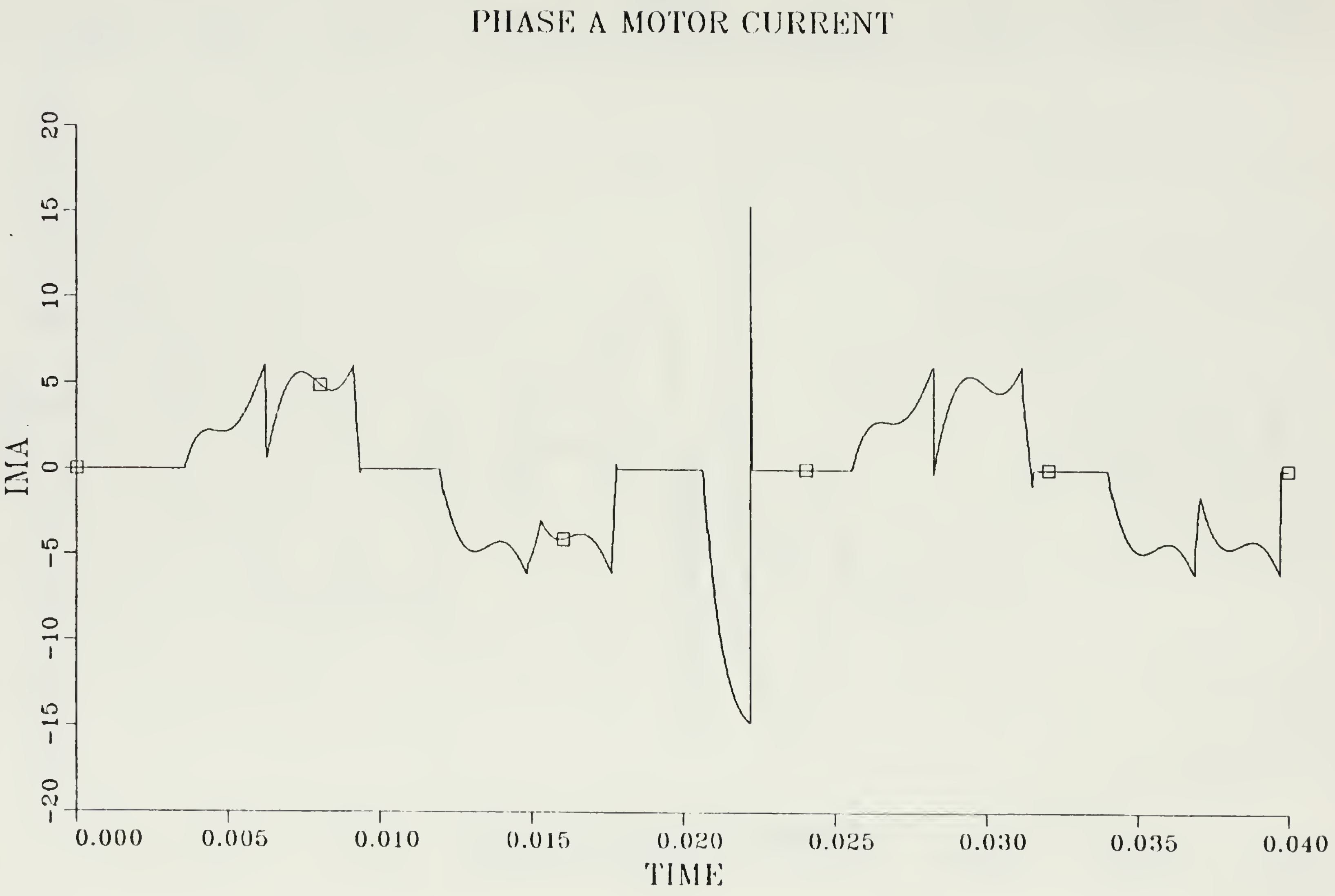


Figure 5.3 Phase A Current showing Reversing Transient

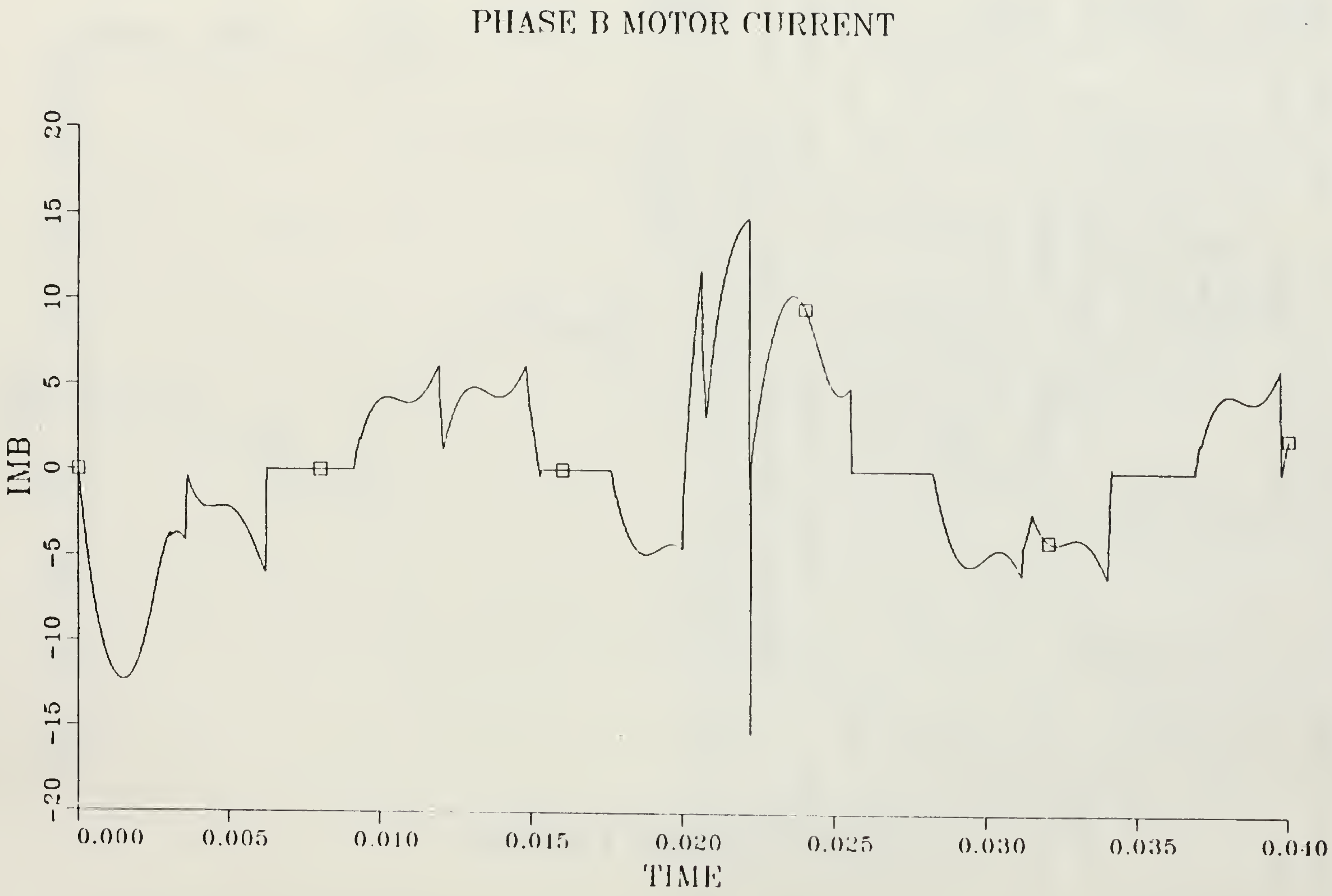


Figure 5.4 Phase B Current showing Reversing Transient

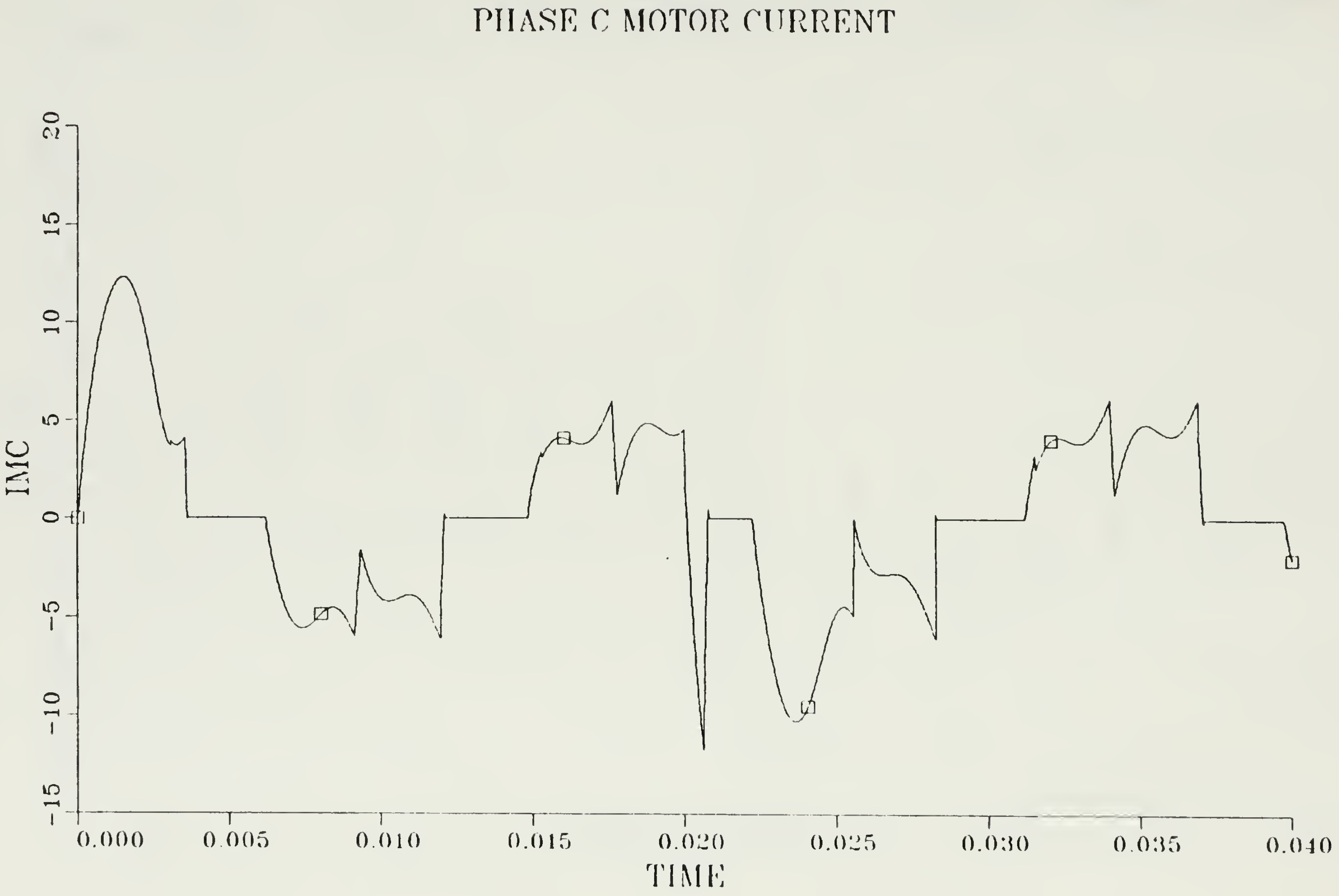


Figure 5.5 Phase C Current showing Reversing Transient

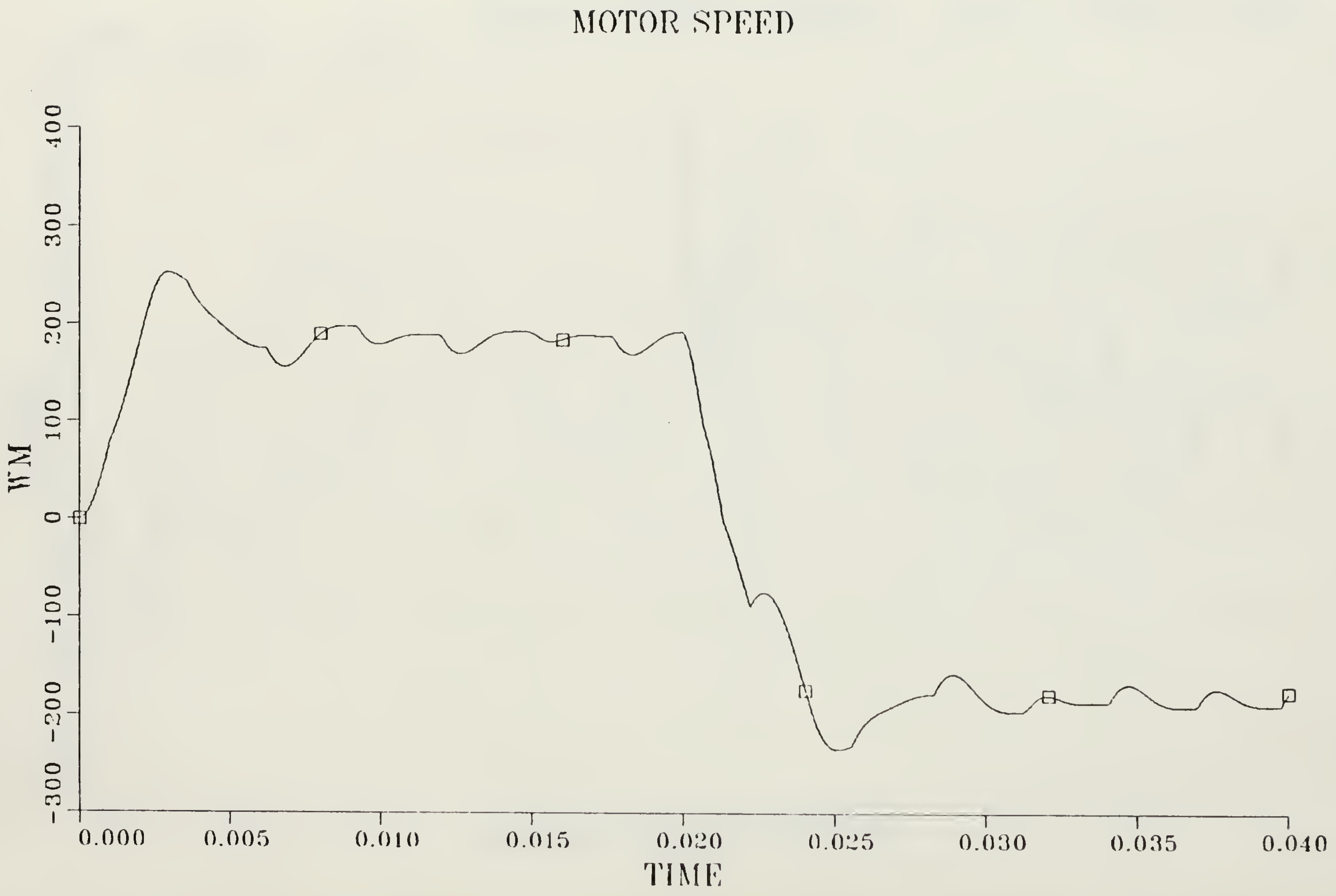


Figure 5.6 Motor Speed during Reversal

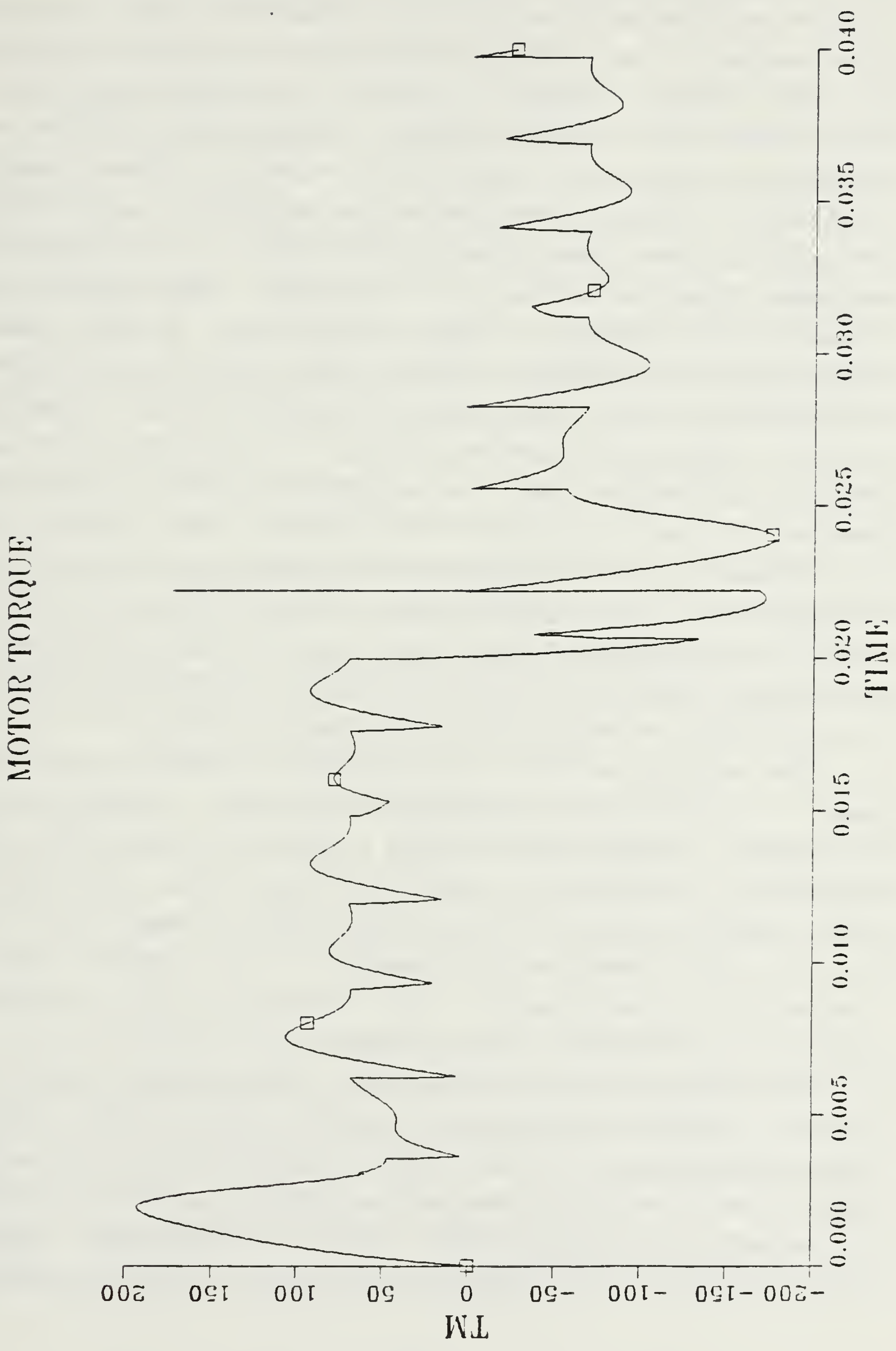


Figure 5.7 Motor Torque during Reversal

In these figures, a demand for reversal is initiated at .02 seconds. Since the rotational inertia of the rotor keeps it rotating in the positive direction for a short time after reverse current begins to flow, a commutation point is reached and the reversal current is switched between phases A and C. As the rotor stops and the motor reverses under the influence of negative torque, the commutation point is again reached but from the opposite direction and the current is switched from phase C to A. There is a large current transient in the figure at this point which is also seen in Figure 5.7 as a transient positive torque, probably due to a combination of the instantaneous nature of the diode model and the transistor time constants. The reality of such a current and torque spike is questionable, but if the dynamic nature of the transistors and diodes used in the power conditioner are not similar, such undesirable transients may be generated, even to the point of punch through of a junction. The effect of the torque spike is seen in Figure 5.6 as a slight interruption of the otherwise smooth transition between forward rotation and reverse rotation.

The simulation can be a powerful analytic and design tool. For example, the addition of damper diodes was seen to maintain current flow during transistor switching (demonstrated in Figures 5.1 and 5.2) which has the effect of maintaining a higher average torque with diodes than without as has been previously discussed. It follows that the faster the diodes operate, the better the motor performance which can be realized in this context.

The availability of the center of the three windings for use as a ground terminal may prove to be advantageous in some applications. The current return path to the power supply provided by the center connection would not be opened by the switching transistors, and the current flow would not be interrupted in the unswitched winding during commutation, resulting in smoother rotation. The design tradeoff to this would be that only half of the supply voltage would be available across any one winding with the center grounded. If the center terminal is left to float, the voltage across two windings is the full supply voltage, but the voltage applied across a single winding and the current through that winding is a function of the back emf voltage generated in both windings. Since the back emf voltage is varying sinusoidally in each winding and one winding is 120 electrical degrees cut of phase with respect to each of the other two windings, a larger proportion of the supply voltage may be applied to one of the conducting coils than the other. The current through the one coil, being equal to the sum of the currents in the other two coils, is at a higher value when the air gap flux is greatest than if the center connection were grounded, and will provide more motor torque. The trajectory of the center connection is shown in Figure 5.8 and can be compared to the single phase flux characteristic in Figure 4.4 and the composite flux variation in Figure 4.6 to see that the voltage aids the current flow in each winding as it comes under the peak of the magnetic flux, as the voltage at the center connection is negative at during the positive flux peaks, and positive during the negative flux peaks, aiding current flow when compared to a grounded center terminal. The relative scale on the ordinate of this figure indicates that the effect is proportional to motor speed.

The fluctuation of motor speed demonstrated by this model has been of the order of ten percent of peak motor speed, somewhat more than in Thomas' simulations [Ref. 1]. This can be attributed to the combination of the transistor switching time constants, the current rise time constant (L/R) and extremely small rotor inertia. If the load inertia was of the order of magnitude of the rotor inertia,

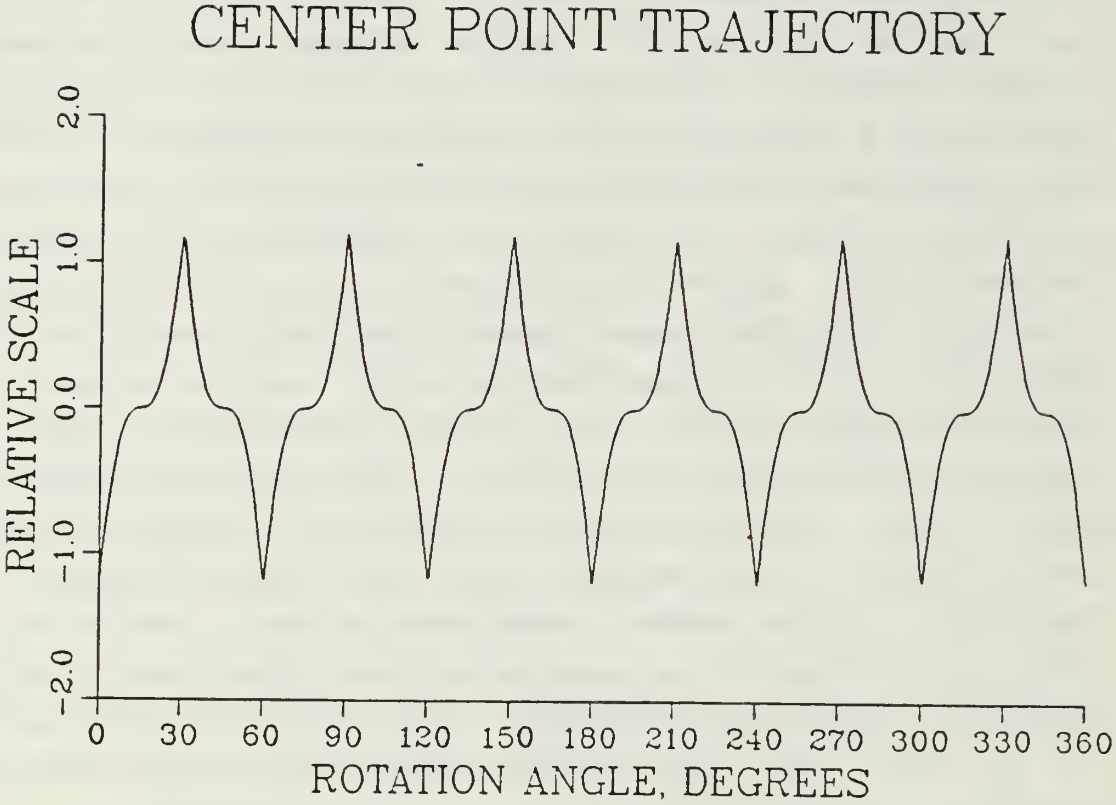


Figure 5.8   Trajectory of Center Connection

the variation in speed would be reduced to the order of five percent due to the increased time constant, (J/B). Additionally, the speed ripple decreases significantly if the applied voltage is increased with no increase in load. With a load torque of 64 inch ounces and a power supply voltage of sixty volts, speed ripple is hardly noticeable at the steady state speed of approximately 4800 rpm due to the increased angular momentum.

With minor changes to the program, different magnetic flux shapes can be simulated and motor performance can be compared. For example, if the stator was designed with interpoles, the flux would take on a flatter shape across the top of the flux curve, which would in turn give different characteristics to the back emf voltage, which could be empirically measured. If the torque coefficient of the motor was known, (it can be measured) the flux distribution could be deduced as it has been for these simulations and the complete motor performance curves predicted. The simulations give a good representation of transient and steady state motor and transistor currents [Ref. 10], from which voltage and current stresses applied to the transistor junctions can be determined. The results of a simulation for a desired steady state load may be analyzed to size the transistors and diodes required for a specific application. Given the heat transfer characteristics of a motor and/or heat sink assembly, the thermal rise of the power conditioner and the motor stator may be predicted by implementing a simple heat transfer model.

From the literature [Ref. 3] it was noted that when some thirty degrees of commutation advance was used to obtain maximum performance from the motors being tested, an increase of 230% over rated horsepower was realized for short periods. This simulation program has the capability of shifting the commutation angles to realize extended performance. This is left for future development of motor performance studies.

VI. CONCLUSION AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSION

The development of a detailed transient model for simulation of the instantaneous performance of a small four pole brushless DC motor supplied by a transistorized power conditioner has been presented. This model was part of a comprehensive development of a fin control actuating system model for the simulation of the dynamic performance of a cruise missile fin controller.

The results of the numerical simulation of the instantaneous motor and power conditioner voltages and currents demonstrated a great deal of correlation to reported experimental test data during steady state operation. The dynamic reversal of the model was performed. The corresponding dynamic currents predicted by the model were analyzed and large transients were demonstrated as would be expected in an actual motor. The conclusion that the model is a good representation of an actual motor and power conditioner drive transistors is supported by all currently available motor data and analytical extensions thereof.

B. RECOMMENDATIONS

This model will be further improved by the addition of delay between the Hall sensors and the commutation algorithm to more realistically simulate the electronic logic of the power conditioner. A routine for the calculation of transistor and diode power dissipation and possibly motor stator heating will be included. This will allow maximum performance to be extracted from the motor and power conditioner for short periods of time without excessive heating.

Additional work on the dynamic magnetic flux profile, particularly in the area of magnetic saturation of the stator iron needs to be investigated and implemented to accurately simulate high power operation.

APPENDIX A

SPACE DEPENDENT FLUX MODEL

Because of the length and complexity of the CSMP model, a simpler model was designed using Digital Simulation Language (DSL). The advantages to DSL include complete compatibility with CSMP and a more or less interactive running capability which the NPS installation of CSMP lacks. If the complete model had been written in DSL, the advantage of quick turnaround of the simulation would have been lost due to the running time of the program. The NPS version of DSL does not have the STIFF integration routine used with CSMP and the Runge-Kutta integration routine in both languages had some computation problems with the fast time constants of the power transistors. The routines contained in this appendix were developed using [Ref. 14 and 15].

```
TITLE THESIS PROJECT
TITLE BRUSHLESS DC MOTOR POWER CONDITIONER
STORAG Z1(500),Z2(500),Z3(500),Z4(500),Z5(500),Z6(500)
INITIAL
CONST PI = 3.14159, VIF=15., VIB = -15.
***************************************
DYNAMIC
***************************************
      THETA = RAMP (0.0)
      THETAD = THETA*180./PI
      BEMFA =(3.*SIN(2.*THETA+(11*PI/6))
     1+.59*SIN(10.*THETA+(1*PI/6)))
      BEMFB =(3.*SIN(2.*THETA+(7*PI/6))
     1+.59*SIN(10.*THETA+(5*PI/6)))
      BEMFC =(3.*SIN(2.*THETA+(3*PI/6))
     1+.59*SIN(10.*THETA+(9*PI/6)))
      ABDIFF= BEMFA - BEMFB
      BCDIFF= BEMFB - BEMFC
      CADIFF= BEMFC - BEMFA
      IF(THETAD .GE. 180.) GO TO 45
      THCON = THETAD
      GO TO 46
45    THCON = THETAD- 180.
46    CONTINUE
      IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
      IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
      IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
      IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
      IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
      IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50   SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      BEMFT = BEMFC - BEMFB
      VN1 = VIF - VEMFC
      VN2 = VIB + VEMFB
      GO TO 60
 51   SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      BEMFT = BEMFA - BEMFB
      VN1 = VIF - VEMFA
      VN2 = VIB + VEMFB
      GO TO 60
 52   SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      BEMFT = BEMFA - BEMFC
      VN1 = VIF - VEMFA
      VN2 = VIB + VEMFC
      GO TO 60
 53   SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      BEMFT = BEMFB - BEMFC
      VN1 = VIF - VEMFB
      VN2 = VIB + VEMFC
      GO TO 60
 54   SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      BEMFT = BEMFB - BEMFA
      VN1 = VIF - VEMFB
      VN2 = VIB + VEMFA
      GO TO 60
 55   SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      BEMFT = BEMFC - BEMFA
      VN1 = VIF - VEMFC
      VN2 = VIB + VEMFA
 60   CONTINUE
      IA = 4.*(SW1-SW2)
      IB = 4.*(SW3-SW4)
      IC = 4.*(SW5-SW6)
*****************************************
SAMPLE
*****************************************
*  GET THE NUMBERS
      Z1(I)= THETAD
      Z2(I)= BEMFA
      Z3(I)= BEMFB
      Z4(I)= BEMFC
      Z5(I)= IA
      Z6(I)= IB
      Z7(I)= IC
      Z8(I)= BEMFT
      WRITE  (30,20)  Z1(I)
      WRITE  (31,20)  Z2(I)
      WRITE  (32,20)  Z3(I)
      WRITE  (33,20)  Z4(I)
      WRITE  (34,20)  Z5(I)
      WRITE  (35,20)  Z6(I)
      WRITE  (36,20)  Z7(I)
      WRITE  (37,20)  Z8(I)
20    FORMAT(F20.6)
      I=I+1
CONTRL FINTIM=6.28, DELT=.01,  DELS=.01
END
STOP
```

Begin DISSPLA program:

```
      REAL Z1(629),Z2(629),Z3(629),Z4(629),Z5(629),Z6(629)
      REAL Z7(629),Z8(629),Z9(629),Z10(629),Z11(629)
      I=0
1     I=I+1
      READ(30,5,END=3) Z1(I)
      READ(31,5,END=3) Z2(I)
      READ(32,5,END=3) Z3(I)
      READ(33,5,END=3) Z4(I)
      READ(34,5,END=3) Z5(I)
      READ(35,5,END=3) Z6(I)
      READ(36,5,END=3) Z7(I)
      READ(37,5,END=3) Z8(I)
5     FORMAT(F20.6)
C
C CONVERSION FROM IN-OZ/AMP TO WEBERS:
      Z2(I) = Z2(I)*2.54*9.8/(100.*16.*2.2)*16.82/5.1393
      Z3(I) = Z3(I)*2.54*9.8/(100.*16.*2.2)*16.82/5.1393
      Z4(I) = Z4(I)*2.54*9.8/(100.*16.*2.2)*16.82/5.1393
      Z5(I) = Z5(I)/60.
      Z6(I) = Z6(I)/60.
      Z7(I) = Z7(I)/60.
      GO TO 1
3     CONTINUE
      CALL TEK618
C     CALL SHERPA ('MACMILLA','A',3)
      CALL PAGE (8.5,11.0)
      CALL NOBRDR
      CALL PHYSOR(1., 5.5)
      CALL AREA2D ( 5.0,2.0)
      CALL COMPLX
      CALL HEADIN ('MAGNETIC FLUX MODEL$',100,1.5,2)
      CALL HEADIN ('PHASE A FLUX$',100,1.,2)
      CALL XNAME ('PHASE B FLUX$',100)
      CALL YNAME ('               $',100)
      CALL XINTAX
      CALL GRAF (0.0,30.,360.,-0.10,'SCALE',0.10)
      CALL CURVE (Z1,Z2,629,0)
      CALL DOT
      CALL CURVE (Z1,Z5,629,0)
      CALL RESET('DOT')
      CALL ENDGR(0)
      CALL PHYSOR(1., 3.25)
      CALL AREA2D ( 5.0,2.0)
      CALL COMPLX
      CALL XNAME ('PHASE C FLUX$',100)
      CALL YNAME ('FLUX, WEBERS$',100)
      CALL XINTAX
      CALL GRAF (0.0,30.,360.,-0.10,'SCALE',0.10)
      CALL CURVE (Z1,Z3,629,0)
      CALL DOT
      CALL CURVE (Z1,Z6,629,0)
      CALL RESET('DOT')
      CALL ENDGR(0)
      CALL PHYSOR(1.,1.)
      CALL AREA2D (5.0,2.0)
      CALL XINTAX
      CALL XNAME ('ROTATION ANGLE, DEGREES$',100)
      CALL YNAME ('               $',100)
      CALL GRAF (0.0,30.,360.,-0.10,'SCALE',0.10)
      CALL CURVE (Z1,Z4,629 ,0)
      CALL DOT
      CALL CURVE (Z1,Z7,629,0)
      CALL RESET('DOT')
      CALL ENDPL(0)
C
      CALL DONEPL
      STOP
      END
```

APPENDIX B

VARIABLE FLUX CSMP PROGRAM LISTINGS

```
* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KTPPP -- THE NORMALIZED PRODUCT OF KT AND THE COMPOSITE VARIABLE FLUX
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* KBPPP -- THE NORMALIZED PRODUCT OF KB AND THE COMPOSITE VARIABLE FLUX
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD (OZ-IN/RAD/S)
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* A2 = J/B     --  THE MECHANICAL TIME CONSTANT OF THE MOTOR
* ABTAU = LA/(RA+REQAB) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*       AND DRIVE TRANSISTORS FOR CURRENT PATH A-B
* BCTAU = LA/(RA+REQBC) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*       AND DRIVE TRANSISTORS FOR CURRENT PATH B-C
* CATAU = LA/(RA+REQCA) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*       AND DRIVE TRANSISTORS FOR CURRENT PATH C-A
* VIF = +SUPPLY VOLTAGE FORWARD DIRECTION
* VIB = +SUPPLY VOLTAGE REVERSE DIRECTION
* VN1 =+SUPPLY VOLTAGE MINUS GENERATED REVERSE VOLTAGE
* VN2 =-SUPPLY VOLTAGE PLUS GENERATED REVERSE VOLTAGE
* RQ#  -- EQUIVALENT CIRCUIT RESISTANCE OF Q(#)
* Q#EXP = EXPONENTIAL MODEL FOR TRANSISTION BETWEEN SATURATION AND CUTOFF
* RSAT = EQUIVALENT CIRCUIT RESISTANCE OF TRANSISTOR SATURATION
* RCUT = EQUIVALENT CIRCUIT RESISTANCE OF TRANSISTOR CUTOFF
* TTIME -- SWITCHING TIME OF TRANSISTOR
*
* THIS VERSION HAS NO DIODES
* VERSION TEN --
* THE PURPOSE OF VERSION TEN IS TO TREAT THE FLUX AS VARYING
* AS THE SUM OF A SINUSOID OF FUNDAMENTAL FREQUENCY
* AND ITS FIFTH HARMONIC AS EXPLAINED IN CHAPTER FOUR.
* CURRENTS ARE NOT SUPERPOSED. FLUX * CURRENT IS COMPUTED FOR EACH PHASE
* AND THE RESULTING TORQUES ARE SUMMED.
* THE TOTAL FLUX IS APPROXIMATED AS THE ALGEBRAIC SUM OF THE FLUX
* ENCOUNTERED BY TWO WINDINGS AT A TIME.
* THIS MODEL SIMULATES MAGNETIC FLUX AS A SINUSOID AND A FIFTH HARMONIC
* AS WELL AS THE SWITCHING LOGIC AND TRANSISTOR COMMUTATION OF A
* BRUSHLESS DC MOTOR. THE WINDINGS ARE NOT TREATED INDEPENDENTLY
* AND THEIR TRANSIENT ELECTRICAL INTERRELATION IS SIMULATED,
* ALTHOUGH THE CONTRIBUTIONS TO DEVELOPED TORQUE ARE
* TREATED AS SUPERPOSABLE.

INITIAL
CONSTANT KT = 16.82, BM = 0.02250, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.11875, PI = 3.14159265, KK3 = 5.1393
PARAMETER LA = .0008, TLL = 64., RA = 0.6850
PARAMETER VSAT = .4, RSAT= .05, RCUT = 1.0E+4, TTIME = 1.0E-6
NOSORT
   BLP = BL/(N**2)
   JLP = JL/(N**2)
   J = JM + JLP
   B = BM + BLP
   A1 = LA / RA
   A2 = J / B
   A3 = LA/(RA +RSAT)
   THRST = 0.0
   JFAC = 0.0
METHOD STIFF
DYNAMIC
   VIF= 15.0 * STEP(0.0)
   VIB =-15.0 * STEP(0.0)
   VIN = VIF - VIB
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
* Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
* AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
* THE LIMITER
   Q1EXP = REALPL(.75, TTIME, 0.75-SW1)
   Q2EXP = REALPL(0.75, TTIME, 0.75-SW2)
   Q3EXP = REALPL(0.75, TTIME, 0.75-SW3)
   Q4EXP = REALPL(0.75, TTIME, 0.75-SW4)
   Q5EXP = REALPL(0.75, TTIME, 0.75-SW5)
   Q6EXP = REALPL(0.75, TTIME, 0.75-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
   RQ1 = LIMIT(RSAT, RCUT, 2.*RCUT*Q1EXP)
   RQ2 = LIMIT(RSAT, RCUT, 2.*RCUT*Q2EXP)
   RQ3 = LIMIT(RSAT, RCUT, 2.*RCUT*Q3EXP)
   RQ4 = LIMIT(RSAT, RCUT, 2.*RCUT*Q4EXP)
   RQ5 = LIMIT(RSAT, RCUT, 2.*RCUT*Q5EXP)
   RQ6 = LIMIT(RSAT, RCUT, 2.*RCUT*Q6EXP)
* TRANSISTOR SWITCHING
   VAN = VN1*RQ2/(RQ1+RQ2) + VN2*RQ1/(RQ1+RQ2)
   VBN = VN1*RQ4/(RQ3+RQ4) + VN2*RQ3/(RQ3+RQ4)
   VCN = VN1*RQ6/(RQ5+RQ6) + VN2*RQ5/(RQ5+RQ6)
* EQUIVALENT RESISTANCE
   REQAB = 2.*RA + RQ3*RQ4/(RQ3+RQ4) + RQ1*RQ2/(RQ1+RQ2)
   REQBC = 2.*RA + RQ3*RQ4/(RQ3+RQ4) + RQ5*RQ6/(RQ5+RQ6)
   REQCA = 2.*RA + RQ1*RQ2/(RQ1+RQ2) + RQ5*RQ6/(RQ5+RQ6)
```

```
* CURRENT CALCULATION
  IAB = (VAN - VBN)/REQAB
  IBC = (VBN - VCN)/REQBC
  ICA = (VCN - VAN)/REQCA
* TIME CONSTANTS
  ABTAU = 2.* LA/REQAB
  BCTAU = 2.* LA/REQBC
  CATAU = 2.* LA/REQCA
* LEG CURRENTS
  IMAB = REALPL(0.0,ABTAU,IAB)
  IMBC = REALPL(0.0,BCTAU,IBC)
  IMCA = REALPL(0.0,CATAU,ICA)
* NET LEG CURRENTS
  IMA = IMAB - IMCA
  IMB = IMBC - IMAB
  IMC = IMCA - IMBC
  DIADT = DERIV(0.0, IMA)
  DIBDT = DERIV(0.0, IMB)
  DICDT = DERIV(0.0, IMC)
  VAO = IMA*(RA)+LA*DIADT+VEMFA
  VBO = IMB*(RA)+LA*DIBDT+VEMFB
  VCO = IMC*(RA)+LA*DICDT+VEMFC
  VO = VN1 + VN2
  VA = VAO - VO
  VB = VBO - VO
  VC = VCO - VO
* PLOT VOLTAGES
  PVA = LIMIT (-60., 60., VA)
  PVB = LIMIT (-60., 60., VB)
  PVC = LIMIT (-60., 60., VC)
* NO DAMPER DIODES
  IQ1 = FCNSW(SW1, .003, .003, IMA)
  IQ2 = FCNSW(SW2, .003, .003, IMA)
  IQ3 = FCNSW(SW3, .003, .003, IMB)
  IQ4 = FCNSW(SW4, .003, .003, IMB)
  IQ5 = FCNSW(SW5, .003, .003, IMC)
  IQ6 = FCNSW(SW6, .003, .003, IMC)
  PQ1 = IQ1 * IQ1 * RQ1
  PQ2 = IQ2 * IQ2 * RQ2
  PQ3 = IQ3 * IQ3 * RQ3
  PQ4 = IQ4 * IQ4 * RQ4
  PQ5 = IQ5 * IQ5 * RQ5
  PQ6 = IQ6 * IQ6 * RQ6
  PQTOT = PQ1 + PQ2 + PQ3 + PQ4 + PQ5 + PQ6
* TORQUE TO MAKE MOTOR TURN
  TA = IMA * KT * BEMFA/KK3
  TB = IMB * KT * BEMFB/KK3
  TC = IMC * KT * BEMFC/KK3
  TM = TA + TB + TC
  TL = REALPL(0.0, .001, TLI)
```

```
   TN2 = TN1 * (1.0/B)
   WM = REALPL(0.0,A2,TN2)
   WMRPM = WM * (30./PI)
   WMRPMR = WMRPM/N
*  THE PHASE ANGLES LOOK CONFUSED BUT THE PHASE RELATIONSHIP IS RIGHT
   BEMFA =(3.*SIN(2.*THETA+(11*PI/6))+.59*SIN(10.*THETA+(1*PI/6)))
   BEMFB =(3.*SIN(2.*THETA+(7*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
   BEMFC =(3.*SIN(2.*THETA+(3*PI/6))+.59*SIN(10.*THETA+(9*PI/6)))
*  NORMALIZE LEG EMF
   VEMFA = BEMFA * KB/KK3 * WM
   VEMFB = BEMFB * KB/KK3 * WM
   VEMFC = BEMFC * KB/KK3 * WM
   VEMFAC = VEMFA-VEMFC
   VEMFBA = VEMFB-VEMFA
   VEMFCB = VEMFC-VEMFB
   THETA = INTGRL(0.0,WM)
   THDEG = THETA * (180.0/PI)
   THCON = THRST
   PWR = WM * TM * .0070615
   KBPPP = KB * BEMFT * (1/KK3)
   KTPPP = KT * BEMFT * (1/KK3)

*  THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
*  DIRECTION.
PROCEDURE TN1=FWDBWD(VIN,TM,TL)
   IF(VIN.LT.0.0) GO TO 10
     TN1 = TM - TL
     GO TO 15
 10  TN1 = TM + TL
 15  CONTINUE
ENDPROCEDURE

*  THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
*  OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
*  SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
     TS = JFAC * 360.0
     THRST = THDEG - TS
     IF(THRST.LT.360.0) GO TO 40
     JFAC = JFAC + 1.0
 40  CONTINUE
ENDPROCEDURE

*  THIS PROCEDURE SIMULATES COUNTERCLOCKWISE COMMUTATION.
*  IT SETS THE VARIABLES SE1 THRU
*  SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
*  OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
*  SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
*  LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
*  IS IMPLEMENTED.
```

```
PRCCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCCN)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CCNTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50 SE1 = 1.
    SE2 = 0.
    SE3 = 1.
    SW1 = 0.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 1.
    SW6 = 0.
    GC TO 60
 51 SE1 = 1.
    SE2 = 0.
    SE3 = 0.
    SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 0.
    SW6 = 0.
    GC TO 60
 52 SE1 = 1.
    SE2 = 1.
    SE3 = 0.
    SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 0.
    SW5 = 0.
    SW6 = 1.
    GC TC 60
 53 SE1 = 0.
    SE2 = 1.
    SE3 = 0.
    SW1 = 0.
    SW2 = 0.
    SW3 = 1.
    SW4 = 0.
    SW5 = 0.
    SW6 = 1.
    GO TO 60
 54 SE1 = 0.
    SE2 = 1.
    SE3 = 1.
    SW1 = 0.
    SW2 = 1.
    SW3 = 1.
    SW4 = 0.
    SW5 = 0.
    SW6 = 0.
    GC TO 60
 55 SE1 = 0.
    SE2 = 0.
    SE3 = 1.
    SW1 = 0.
    SW2 = 1.
    SW3 = 0.
    SW4 = 0.
    SW5 = 1.
    SW6 = 0.
    GO TO 60
 60 CCNTINUE
ENDPRCCEDURE

* THE FOLLOWING PRCCEDURE HAS THE SAME FORM AND EFFECT AS THE
* PREVIOUS.  IT IS USED HERE TO DETERMINE THE ALGEBRAIC SUM CF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE FLUX (BEMFT). THIS FUNCTION COULD AS EASILY
* HAVE BEEN CALCULATED IN THE PREVIOUS PROCEDURE EXCEPT THAT IT
* COULD NOT ACCOMODATE THE ADDITIONAL VARIABLES.
PRCCEDURE BEMFT,VN1,VN2=VOLT(THCON,BEMFA,BEMFB,BEMFC,VEMFA,VEMFB,VEMFC)
   IF(THCON .GE.180.) GO TO 65
   GO TO 66
65  THCON = THCON - 180.
66 CCNTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 70
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 71
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 72
   IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 73
   IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 74
   IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 75
 70 BEMFT = BEMFC - BEMFB
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFB
    GC TO 80
 71 BEMFT = BEMFA - BEMFB
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFB
    GC TO 80
 72 BEMFT = BEMFA - BEMFC
```

```
   VN1 = VIF - VEMFA
   VN2 = VIB - VEMFC
   GO TO 80
73 BEMFT = BEMFB - BEMFC
   VN1 = VIF - VEMFB
   VN2 = VIB - VEMFC
   GO TO 80
74 BEMFT = BEMFB - BEMFA
   VN1 = VIF - VEMFB
   VN2 = VIB - VEMFA
   GO TO 80
75 BEMFT = BEMFC - BEMFA
   VN1 = VIF - VEMFC
   VN2 = VIB - VEMFA
80 CONTINUE
ENDPROCEDURE


TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .20E-4, PRDEL = .002, DELMIN =1.0E-10
  FINISH THRST = 359.5
  PRINT WM, WMRPM, THRST, VAN, VBN, VCN, VA, VB, VC, ...
   IAB, IBC, ICA,...
   BEMFA, BEMFB, BEMFC, BEMFT, ...
   IMAB, IMBC, IMCA, IMA, IMB, IMC, IMT, DIADT, DIBDT, DICDT,...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6,...
   PQ1,PQ2,PQ3,PQ4,PQ5,PQ6,PQTOT, PWRDSS,PWR, ...
   TM, TL
  RANGE DELT
  PREPARE WM, TM, TL, WMRPM, THRST, PVA, PVB, PVC, IMAB, IMBC, IMCA,...
   IMA, IMB, IMC, IMT, DIADT, DIBDT, DICDT,...
   VEMFA, VEMFB, VEMFC, BEMFT, ...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6, KBPPP
  LABEL PHASE A MOTOR CURRENT, BACK EMF A-C
  OUTPUT TIME, IMA, VEMFAC
  PAGE XYPLOT
       END
  RESET PRINT
  LABEL PHASE C MOTOR CURRENT, BACK EMF C-B
  OUTPUT TIME, IMC, VEMFCB
  PAGE XYPLOT
       END
  RESET PRINT
  LABEL PHASE B MOTOR CURRENT, BACK EMF B-A
  OUTPUT TIME, IMB, VEMFBA
  PAGE XYPLOT
       END
  LABEL  MOTOR SPEED
  OUTPUT TIME, WM
```

```
    PAGE XYPLOT
         END
   ENDJOB
```

```
* THIS VERSION HAS DIODES
* VERSION TEN C--
* THIS MODEL SIMULATES BACK EMF AS A SINUSOID AND A FIFTH HARMONIC,
* AND SIMULATES DIODE COMMUTATION AS WELL AS THE SWITCHING LOGIC AND
* TRANSISTOR DYNAMICS OF A BRUSHLESS DC MOTOR POWER CONDITIONER.
INITIAL
CONSTANT KT = 16.82, BM = 0.02250, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.11875, PI = 3.14159265, KK3 = 5.1393
PARAMETER LA = .0008, TLL = 64., RA = 0.6850
PARAMETER VSAT = .4, RSAT= .05, RCUT = 1.0E+4, TTIME = 1.0E-6
NOSORT
   BLP = BL/(N**2)
   JLP = JL/(N**2)
   J = JM + JLP
   B = BM + BLP
   A1 = LA / RA
   A2 = J / B
   A3 = LA/(RA +RSAT)
   THRST = 0.0
   JFAC = 0.0
METHOD STIFF
DYNAMIC
   VIF= 15.0 * STEP(0.0)
   VIB =-15.0 * STEP(0.0)
   VIN = VIF - VIB
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
* Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
* AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
* THE LIMITER
   Q1EXP = REALPL(.75, TTIME, 0.75-SW1)
   Q2EXP = REALPL(0.75, TTIME, 0.75-SW2)
   Q3EXP = REALPL(0.75, TTIME, 0.75-SW3)
   Q4EXP = REALPL(0.75, TTIME, 0.75-SW4)
   Q5EXP = REALPL(0.75, TTIME, 0.75-SW5)
   Q6EXP = REALPL(0.75, TTIME, 0.75-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
   RQ1 = LIMIT(RSAT, RCUT, 2.*RCUT*Q1EXP)
   RQ2 = LIMIT(RSAT, RCUT, 2.*RCUT*Q2EXP)
   RQ3 = LIMIT(RSAT, RCUT, 2.*RCUT*Q3EXP)
   RQ4 = LIMIT(RSAT, RCUT, 2.*RCUT*Q4EXP)
   RQ5 = LIMIT(RSAT, RCUT, 2.*RCUT*Q5EXP)
   RQ6 = LIMIT(RSAT, RCUT, 2.*RCUT*Q6EXP)
* LINEAR DIODE MODEL
   RD1 = FCNSW(VN1 - VA, RSAT, RCUT, RCUT)
   RD2 = FCNSW(VN2 - VA, RCUT, RCUT, RSAT)
   RD3 = FCNSW(VN1 - VB, RSAT, RCUT, RCUT)
   RD4 = FCNSW(VN2 - VB, RCUT, RCUT, RSAT)
   RD5 = FCNSW(VN1 - VC, RSAT, RCUT, RCUT)
```

```
      RD6 = FCNSW(VN2 - VC, RCUT, RCUT, RSAT)
*     TRANSISTOR SWITCHING
      VAN = VN1*RQ2/(RQ1+RQ2) + VN2*RQ1/(RQ1+RQ2)
      VBN = VN1*RQ4/(RQ3+RQ4) + VN2*RQ3/(RQ3+RQ4)
      VCN = VN1*RQ6/(RQ5+RQ6) + VN2*RQ5/(RQ5+RQ6)
*     EQUIVALENT RESISTANCE
      REQA1 = RQ1 * RD1/(RQ1+RD1)
      REQA2 = RQ2 * RD2/(RQ2+RD2)
      REQB1 = RQ3 * RD3/(RQ3+RD3)
      REQB2 = RQ4 * RD4/(RQ4+RD4)
      REQC1 = RQ5 * RD5/(RQ5+RD5)
      REQC2 = RQ6 * RD6/(RQ6+RD6)
      REQA = REQA1 * REQA2/(REQA1+REQA2)
      REQB = REQB1 * REQB2/(REQB1+REQB2)
      REQC = REQC1 * REQC2/(REQC1+REQC2)
      REQAB = 2.*RA + REQA + REQB
      REQBC = 2.*RA + REQB + REQC
      REQCA = 2.*RA + REQC + REQA
      IAB = (VAN - VBN)/REQAB
      IBC = (VBN - VCN)/REQBC
      ICA = (VCN - VAN)/REQCA
*     TIME CONSTANTS
      ABTAU = 2.* LA/REQAB
      BCTAU = 2.* LA/REQBC
      CATAU = 2.* LA/REQCA
*     LEG CURRENTS
      IMAB = REALPL(0.0,ABTAU,IAB)
      IMBC = REALPL(0.0,BCTAU,IBC)
      IMCA = REALPL(0.0,CATAU,ICA)
*     NET LEG CURRENTS
      IMA = IMAB - IMCA
      IMB = IMBC - IMAB
      IMC = IMCA - IMBC
      DIADT = DERIV(0.0, IMA)
      DIBDT = DERIV(0.0, IMB)
      DICDT = DERIV(0.0, IMC)
      VO = VN1 + VN2
      VAO = IMA*(RA)+LA*DIADT+VEMFA
      VBO = IMB*(RA)+LA*DIBDT+VEMFB
      VCO = IMC*(RA)+LA*DICDT+VEMFC
      VA = VAO - VO
      VB = VBO - VO
      VC = VCO - VO
      PVA = LIMIT (-60., 60., VA)
      PVB = LIMIT (-60., 60., VB)
      PVC = LIMIT (-60., 60., VC)
      PVAC = PVA-PVC
      PVBA = PVB-PVA
      PVCB = PVC-PVB
*     VOLTAGES ACROSS TRANSISTORS AND DIODES
```

```
      VQ1 = VIF - VA
      VQ2 = VA - VIB
      VQ3 = VIF - VB
      VQ4 = VB - VIB
      VQ5 = VIF - VC
      VQ6 = VC - VIB
      IQ1 = FCNSW(SW1, .003, .003, IMA)
      IQ2 = FCNSW(SW2, .003, .003, IMA)
      IQ3 = FCNSW(SW3, .003, .003, IMB)
      IQ4 = FCNSW(SW4, .003, .003, IMB)
      IQ5 = FCNSW(SW5, .003, .003, IMC)
      IQ6 = FCNSW(SW6, .003, .003, IMC)
      PQ1 = VQ1 * IQ1
      PQ2 = VQ2 * IQ2
      PQ3 = VQ3 * IQ3
      PQ4 = VQ4 * IQ4
      PQ5 = VQ5 * IQ5
      PQ6 = VQ6 * IQ6
      PQTOT = PQ1 + PQ2 + PQ3 + PQ4 + PQ5 + PQ6
*     THE PHASE ANGLES LOOK CONFUSED BUT THE PHASE RELATIONSHIP IS RIGHT
      BEMFA =(3.*SIN(2.*THETA+(11*PI/6))+.59*SIN(10.*THETA+(1*PI/6)))
      BEMFB =(3.*SIN(2.*THETA+(7*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
      BEMFC =(3.*SIN(2.*THETA+(3*PI/6))+.59*SIN(10.*THETA+(9*PI/6)))
*     NORMALIZE LEG EMF
      VEMFA = BEMFA * KB/KK3 * WM
      VEMFB = BEMFB * KB/KK3 * WM
      VEMFC = BEMFC * KB/KK3 * WM
      VEMFAC = VEMFA-VEMFC
      VEMFBA = VEMFB-VEMFA
      VEMFCB = VEMFC-VEMFB
*     TORQUE TO MAKE MOTOR TURN
      TA = IMA * KT * BEMFA/KK3
      TB = IMB * KT * BEMFB/KK3
      TC = IMC * KT * BEMFC/KK3
      TM = TA + TB + TC
      TL = TLL*STEP(1.0E-3)
      TN2 = TN1 * (1.0/B)
      WM = REALPL(0.1,A2,TN2)
      WMRPM = WM * (30./PI)
      WMRPMR = WMRPM/N
      THETA = INTGRL(0.0,WM)
      THDEG = THETA * (180.0/PI)
      THCCN = THRST
      PWR = WM * TM * .0070615
      IL = VIN/(2*RCUT)
      PWRDSS = 2.*VSAT*IMT + 4.*RCUT*IL**2
*     COMPOSITE COEFFICIENTS
      KBPPP = KB * BEMFT * (1/KK3)
      KTPPP = KT * BEMFT * (1/KK3)
```

```
* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.
PRCCEDURE TN1=FWDBWD(VIN,TM,TL)
  IF(VIN.LT.0.0) GC TO 10
    TN1 = TM - TL
    GO TO 15
 10 TN1 = TM + TL
 15 CCNTINUE
ENDPRCCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* CF MECHANICAL RCTATION.  THIS IS FUNDAMENTAL TO THE SIMULATICN OF ALL
* SWITCHING AND PCSITION SENSING ACTION.

PRCCEDURE THRST=RESET(JFAC,THDEG)
    TS = JFAC * 360.0
    THRST = THDEG - TS
    IF(THRST.LT.360.0) GO TC 40
    JFAC = JFAC + 1.0
 40 CONTINUE
ENDPRCCEDURE

* THIS PROCEDURE SIMULATES COUNTERCLOCKWISE COMMUTATION.
* IT SETS THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* CF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.
PRCCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCCN)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CCNTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCCN .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50 SE1 = 1.
    SE2 = 0.
    SE3 = 1.
    SW1 = 0.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 1.
    SW6 = 0.
    GC TO 60
```

```
51 SE1 = 1.
   SE2 = 0.
   SE3 = 0.
   SW1 = 1.
   SW2 = 0.
   SW3 = 0.
   SW4 = 1.
   SW5 = 0.
   SW6 = 0.
   GO TO 60
52 SE1 = 1.
   SE2 = 1.
   SE3 = 0.
   SW1 = 1.
   SW2 = 0.
   SW3 = 0.
   SW4 = 0.
   SW5 = 0.
   SW6 = 1.
   GO TO 60
53 SE1 = 0.
   SE2 = 1.
   SE3 = 0.
   SW1 = 0.
   SW2 = 0.
   SW3 = 1.
   SW4 = 0.
   SW5 = 0.
   SW6 = 1.
   GO TO 60
54 SE1 = 0.
   SE2 = 1.
   SE3 = 1.
   SW1 = 0.
   SW2 = 1.
   SW3 = 1.
   SW4 = 0.
   SW5 = 0.
   SW6 = 0.
   GO TO 60
55 SE1 = 0.
   SE2 = 0.
   SE3 = 1.
   SW1 = 0.
   SW2 = 1.
   SW3 = 0.
   SW4 = 0.
   SW5 = 1.
   SW6 = 0.
   GO TO 60
```

```
 60 CONTINUE
ENDPROCEDURE

* THE FOLLOWING PROCEDURE HAS THE SAME FORM AND EFFECT AS THE
* PREVIOUS.  IT IS USED HERE TO DETERMINE THE ALGEBRAIC SUM OF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE FLUX (BEMFT). THIS FUNCTION COULD AS EASILY
* HAVE BEEN CALCULATED IN THE PREVIOUS PROCEDURE EXCEPT THAT IT
* COULD NOT ACCOMODATE THE ADDITIONAL VARIABLES.
PROCEDURE BEMFT,VN1,VN2=VOLT(THCON,BEMFA,BEMFB,BEMFC,VEMFA,VEMFB,VEMFC)
  IF(THCON .GE. 180.) GO TO 65
  GO TO 66
65  THCON = THCON - 180.
66 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 70
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 71
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 72
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 73
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 74
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 75
 70 BEMFT = BEMFC - BEMFB
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFB
    GO TO 80
 71 BEMFT = BEMFA - BEMFB
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFB
    GO TO 80
 72 BEMFT = BEMFA - BEMFC
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFC
    GO TO 80
 73 BEMFT = BEMFB - BEMFC
    VN1 = VIF - VEMFB
    VN2 = VIB - VEMFC
    GO TO 80
 74 BEMFT = BEMFB - BEMFA
    VN1 = VIF - VEMFB
    VN2 = VIB - VEMFA
    GO TO 80
 75 BEMFT = BEMFC - BEMFA
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFA
 80 CONTINUE
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .20E-4, PRDEL = .002, DELMIN =1.0E-10
  FINISH THRST = 359.5
  PRINT WM, WMRPM, THRST, ...
   VAN, VBN, VCN, VA, VB, VC, ...
   IAB, IBC, ICA,...
   VEMFA, VEMFB, VEMFC, ...
   IMAB, IMBC, IMCA, IMA, IMB, IMC, DIADT, DIBDT, DICDT,...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6,...
   TM, TL
  LABEL PHASE C MOTOR CURRENT, VOLTAGE A-C
  OUTPUT TIME, IMC, PVAC
  PAGE XYPLOT
       END
  RESET PRINT
  LABEL PHASE A MOTOR CURRENT, VOLTAGE B-A
  OUTPUT TIME, IMA, PVBA
  PAGE XYPLOT
       END
  LABEL MOTOR TORQUE
  OUTPUT THRST, TA, TB, TC
  PAGE XYPLOT
       END
  LABEL  MOTOR SPEED
  OUTPUT TIME, WM
  PAGE XYPLOT
       END
ENDJOB
```

```
* PATCHES FROM 10C INSTALLED
* VERSION ELEVEN --
* THIS VERSION INCORPORATES REVERSING COMMUTATION AT REVTIM.
* THIS MODEL SIMULATES MAGNETIC FLUX AS A SINUSOID AND A FIFTH
* HARMONIC AND SIMULATES DIODE COMMUTATION AS WELL AS THE SWITCHING
* LOGIC AND TRANSISTOR DYNAMICS OF A BRUSHLESS DC MOTOR POWER
* CONDITIONER.
* THIS VERSION WILL RUN IN EITHER DIRECTION AND INCORPORATES A SUPERIOR
* METHOD FOR RESETTING THRST EVERY 360 DEGREES.  BIDIRECTIONAL
* COMMUTATION ROUTINES ARE INCORPORATED AND THE HALL SENSORS
* HAVE A ROUTINE OF THEIR OWN.
INITIAL
CONSTANT KT = 16.82, BM = 0.02250, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.11875, PI = 3.14159265, KK3 = 5.3821
PARAMETER LA = .0008, RA = 0.6850, TLL= 64.
PARAMETER VSAT = .4, RSAT= .05, RCUT = 1.0E+4
PARAMETER TTIME = 1.0E-6, REVTIM = 0.02
NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
  A2 = J / B
  A3 = LA/(RA +RSAT)
  THRST = 0.0
  JFAC = 0.0
METHOD STIFF
DYNAMIC
  VIF= 15.0 * STEP(0.0)
  VIB =-15.0 * STEP(0.0)
  VIN = VIF - VIB
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
* Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
* AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
* THE LIMITER
  Q1EXP = REALPL(.75, TTIME, 0.75-SW1)
  Q2EXP = REALPL(0.75, TTIME, 0.75-SW2)
  Q3EXP = REALPL(0.75, TTIME, 0.75-SW3)
  Q4EXP = REALPL(0.75, TTIME, 0.75-SW4)
  Q5EXP = REALPL(0.75, TTIME, 0.75-SW5)
  Q6EXP = REALPL(0.75, TTIME, 0.75-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
  RQ1 = LIMIT(RSAT, RCUT, 2.*RCUT*Q1EXP)
  RQ2 = LIMIT(RSAT, RCUT, 2.*RCUT*Q2EXP)
  RQ3 = LIMIT(RSAT, RCUT, 2.*RCUT*Q3EXP)
  RQ4 = LIMIT(RSAT, RCUT, 2.*RCUT*Q4EXP)
  RQ5 = LIMIT(RSAT, RCUT, 2.*RCUT*Q5EXP)
  RQ6 = LIMIT(RSAT, RCUT, 2.*RCUT*Q6EXP)
* LINEAR DIODE MODEL
  RD1 = FCNSW(VN1 - VA, RSAT, RCUT, RCUT)
  RD2 = FCNSW(VN2 - VA, RCUT, RCUT, RSAT)
  RD3 = FCNSW(VN1 - VB, RSAT, RCUT, RCUT)
  RD4 = FCNSW(VN2 - VB, RCUT, RCUT, RSAT)
  RD5 = FCNSW(VN1 - VC, RSAT, RCUT, RCUT)
  RD6 = FCNSW(VN2 - VC, RCUT, RCUT, RSAT)
* TRANSISTOR SWITCHING
  VAN = VN1*RQ2/(RQ1+RQ2) + VN2*RQ1/(RQ1+RQ2)
  VBN = VN1*RQ4/(RQ3+RQ4) + VN2*RQ3/(RQ3+RQ4)
  VCN = VN1*RQ6/(RQ5+RQ6) + VN2*RQ5/(RQ5+RQ6)
* EQUIVALENT RESISTANCE
  REQA1 = RQ1 * RD1/(RQ1+RD1)
  REQA2 = RQ2 * RD2/(RQ2+RD2)
  REQB1 = RQ3 * RD3/(RQ3+RD3)
  REQB2 = RQ4 * RD4/(RQ4+RD4)
  REQC1 = RQ5 * RD5/(RQ5+RD5)
  REQC2 = RQ6 * RD6/(RQ6+RD6)
  REQA = REQA1 * REQA2/(REQA1+REQA2)
  REQB = REQB1 * REQB2/(REQB1+REQB2)
  REQC = REQC1 * REQC2/(REQC1+REQC2)
  REQAB = 2.*RA + REQA + REQB
  REQBC = 2.*RA + REQB + REQC
  REQCA = 2.*RA + REQC + REQA
  IAB = (VAN - VBN)/REQAB
  IBC = (VBN - VCN)/REQBC
  ICA = (VCN - VAN)/REQCA
* TIME CONSTANTS
  ABTAU = 2.* LA/REQAB
  BCTAU = 2.* LA/REQBC
  CATAU = 2.* LA/REQCA
* LEG CURRENTS
  IMAB = REALPL(0.0,ABTAU,IAB)
  IMBC = REALPL(0.0,BCTAU,IBC)
  IMCA = REALPL(0.0,CATAU,ICA)
* NET LEG CURRENTS
  IMA = IMAB - IMCA
  IMB = IMBC - IMAB
  IMC = IMCA - IMBC
  DIADT = DERIV(0.0, IMA)
  DIBDT = DERIV(0.0, IMB)
  DICDT = DERIV(0.0, IMC)
  VO = VN1 + VN2
  VAO = IMA*(RA)+LA*DIADT+VEMFA
  VBO = IMB*(RA)+LA*DIBDT+VEMFB
  VCO = IMC*(RA)+LA*DICDT+VEMFC
  VA = VAO - VO
  VB = VBO - VO
  VC = VCO - VO
  PVA = LIMIT (-60., 60., VA)
  PVB = LIMIT (-60., 60., VB)
  PVC = LIMIT (-60., 60., VC)
  PVAC = PVA-PVC
  PVBA = PVB-PVA
  PVCB = PVC-PVB
* VOLTAGES ACROSS TRANSISTORS AND DIODES
  VQ1 = VIF - VA
  VQ2 = VA - VIB
  VQ3 = VIF - VB
  VQ4 = VB - VIB
  VQ5 = VIF - VC
  VQ6 = VC - VIB
  IQ1 = FCNSW(SW1, .003, .003, IMA)
  IQ2 = FCNSW(SW2, .003, .003, IMA)
  IQ3 = FCNSW(SW3, .003, .003, IMB)
  IQ4 = FCNSW(SW4, .003, .003, IMB)
  IQ5 = FCNSW(SW5, .003, .003, IMC)
  IQ6 = FCNSW(SW6, .003, .003, IMC)
  PQ1 = VQ1 * IQ1
  PQ2 = VQ2 * IQ2
  PQ3 = VQ3 * IQ3
  PQ4 = VQ4 * IQ4
  PQ5 = VQ5 * IQ5
  PQ6 = VQ6 * IQ6
  PQTOT = PQ1 + PQ2 + PQ3 + PQ4 + PQ5 + PQ6
* THE PHASE ANGLES LOOK CONFUSED BUT THE PHASE RELATIONSHIP IS RIGHT
  BEMFA =(3.*SIN(2.*THETA+(11*PI/6))+.59*SIN(10.*THETA+(1*PI/6)))
  BEMFB =(3.*SIN(2.*THETA+(7*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
  BEMFC =(3.*SIN(2.*THETA+(3*PI/6))+.59*SIN(10.*THETA+(9*PI/6)))
* NORMALIZE LEG EMF
  VEMFA = BEMFA * KB/KK3 * WM
  VEMFB = BEMFB * KB/KK3 * WM
  VEMFC = BEMFC * KB/KK3 * WM
  VEMFAC = VEMFA-VEMFC
  VEMFBA = VEMFB-VEMFA
  VEMFCB = VEMFC-VEMFB
* TORQUE TO MAKE MOTOR TURN
  TA = IMA * KT * BEMFA/KK3
  TB = IMB * KT * BEMFB/KK3
  TC = IMC * KT * BEMFC/KK3
  TM = TA + TB + TC
  TL = TLL*STEP(1.0E-3)
  TN2 = TN1 * (1.0/B)
  WM = REALPL(0.1,A2,TN2)
  WMRPM = WM * (30./PI)
  WMRPMR = WMRPM/N
  THETA = INTGRL(0.0,WM)
  THDEG = THETA * (180.0/PI)
  THCON = THRST
  PWR = WM * TM * .0070615
  IL = VIN/(2*RCUT)
  PWRDSS = 2.*VSAT*IMT + 4.*RCUT*IL**2
* COMPOSITE COEFFICIENTS
  KBPPP = KB * BEMFT * (1/KK3)
  KTPPP = KT * BEMFT * (1/KK3)

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.
PROCEDURE TN1=FWDBWD(WM,TM,TL)
  IF(WM.LT.0.0) GO TO 1
     TN1 = TM - TL
     GO TO 5
 1   TN1 = TM + TL
 5   CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
     THRST = AMOD(THDEG, 360.)
     IF(THRST .LT. 0.0) THRST = THRST + 360.
ENDPROCEDURE

* THIS PROCEDURE WAS TAKEN FROM THE NEXT PROCEDURE BECAUSE THE HALL
* SENSORS SHOULD GENERATE A SINGLE VALUED FUNCTION OF POSITION
* REGARDLESS OF DIRECTION OF ROTATION
PROCEDURE SE1,SE2,SE3=HALL(THCON)
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 10
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 11
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 12
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 13
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 14
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 15
 10  SE1 = 1.
     SE2 = 0.
     SE3 = 1.
     GOTO 20
 11  SE1 = 1.
     SE2 = 0.
     SE3 = 0.
     GOTO 20
 12  SE1 = 1.
     SE2 = 1.
     SE3 = 0.
     GOTO 20
 13  SE1 = 0.
     SE2 = 1.
     SE3 = 0.
```

```
      GCTO 20
   14 SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      GCTO 20
   15 SE1 = 0.
      SE2 = 0.
      SE3 = 1.
   20 CCNTINUE
ENDPROCEDURE

* THIS PROCEDURE SIMULATES GENERAL COMMUTATION. SW1 THRU SW6
* SIMULATE POWER TRANSISTOR TRIGGERS BEING ENERGIZED OR SWITCHED OFF
* THCCN IS THE VARIABLE THRCUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED. REVTIM IS THE TIME AT WHICH CLOCKWISE COMMUTATION
* EEGINS.
PROCEDURE SW1,SW2,SW3,SW4,SW5,SW6=COMM(TIME,REVTIM,THCCN)
   IF(TIME .GT.REVTIM ) GO TC 100
   IF(THCON .GE.180.) GO TO 45
   GO TO 46
45  THCCN = THCON - 180.
46 CONTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
   IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
   IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
   IF(THCON .GE.150..AND. THCON .LT.180.) GO TC 55
* CLOCKWISE COMMUTATION
100  IF(THCON .GE.180.) GO TO 145
   GO TO 146
145  THCON = THCON - 180.
146 CCNTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 53
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 54
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 55
   IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 50
   IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 51
   IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 52
   50 SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      GC TO 60
   51 SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
 52   SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 53   SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 54   SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
 55   SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
 60   CONTINUE
ENDPROCEDURE

* THE FOLLOWING PROCEDURE HAS THE SAME FORM AND EFFECT AS THE
* PREVIOUS.  IT IS USED HERE TO DETERMINE THE ALGEBRAIC SUM OF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE FLUX (BEMFT). IT ALSO SUBTRACTS THE GENERATED
* VOLTAGE FROM THE PROPER SUPPLY VOLTAGE.
* THIS FUNCTION COULD AS EASILY
* HAVE BEEN CALCULATED IN THE PREVIOUS PROCEDURE EXCEPT THAT IT
* COULD NOT ACCOMODATE THE ADDITIONAL VARIABLES.
PROCEDURE BEMFT,VN1,VN2=VOLT(THCON,BEMFA,BEMFB,BEMFC,VEMFA,VEMFB,VEMFC)
  IF(TIME .GT.REVTIM ) GO TO 200
  IF(THCON .GE.180.) GO TO 65
  GO TO 66
65  THCON = THCON - 180.
66 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 70
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 71
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 72
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 73
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 74
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 75
* CLOCKWISE COMMUTATION
200  IF(THCON .GE.180.) GO TO 245
  GO TO 246
245  THCON = THCON - 180.
246 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 73
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 74
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 75
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 70
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 71
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 72
 70 BEMFT = BEMFC - BEMFB
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFB
    GO TO 80
 71 BEMFT = BEMFA - BEMFB
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFB
    GO TO 80
 72 BEMFT = BEMFA - BEMFC
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFC
    GO TO 80
 73 BEMFT = BEMFB - BEMFC
    VN1 = VIF - VEMFB
    VN2 = VIB - VEMFC
    GO TO 80
 74 BEMFT = BEMFB - BEMFA
    VN1 = VIF - VEMFB
    VN2 = VIB - VEMFA
    GO TO 80
 75 BEMFT = BEMFC - BEMFA
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFA
 80 CONTINUE
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .20E-4, PRDEL = .002, DELMIN =1.0E-10
  FINISH THRST = -359.5
  PRINT WM, WMRPM, THRST, ...
   VAN, VBN, VCN, VA, VB, VC, ...
   IAB, IBC, ICA,...
   VEMFA, VEMFB, VEMFC, ...
   IMAB, IMBC, IMCA, IMA, IMB, IMC, DIADT, DIBDT, DICDT,...
```

```
      RQ1, RQ2, RQ3, RQ4,RQ5, RQ6,...
      TM, TL
     LABEL PHASE C MOTOR CURRENT
     OUTPUT TIME, IMC
     PAGE XYPLOT
          END
     RESET PRINT
     LABEL PHASE B MOTOR CURRENT
     OUTPUT TIME, IMB
     PAGE XYPLOT
          END
     LABEL PHASE A MOTOR CURRENT
     OUTPUT TIME, IMA
     PAGE XYPLOT
          END
     LABEL MOTOR SPEED
     OUTPUT TIME, WM
     PAGE XYPLOT
          END
     LABEL MOTOR TORQUE
     OUTPUT TIME, TM
     PAGE XYPLOT
          END
          STOP
   ENDJOB
```

APPENDIX C

CONSTANT FLUX CSMP PROGRAM LISTINGS

```
* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* A1 = LA/RA   --  THE ELECTRICAL TIME CONSTANT OF THE MOTOR
* A2 = J/B     --  THE MECHANICAL TIME CONSTANT OF THE MOTOR
* A3 = LA/(RA+RSAT) THE ELECTRICAL TIME CONSTANT OF THE MOTOR AND
*      DRIVE TRANSISTORS
* VIF = +SUPPLY VOLTAGE FORWARD DIRECTION
* VIB = +SUPPLY VOLTAGE REVERSE DIRECTION
* VIN1 =+SUPPLY VOLTAGE MINUS GENERATED REVERSE VOLTAGE
* VIN2 =-SUPPLY VOLTAGE PLUS GENERATED REVERSE VOLTAGE
* IPOS, INEG = RESISTIVE CONTROLLER CURRENT TO WINDINGS
* RSAT = SATURATION RESISTANCE OF CONTROLLER TRANSISTOR
* RCUT = CUTOFF RESISTANCE OF CONTROLLER TRANSISTOR
* ABTAU = LA/(RA+REQAB) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*         AND DRIVE TRANSISTORS FOR CURRENT PATH A-B
* BCTAU = LA/(RA+REQBC) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*         AND DRIVE TRANSISTORS FOR CURRENT PATH B-C
* CATAU = LA/(RA+REQCA) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*         AND DRIVE TRANSISTORS FOR CURRENT PATH C-A
* VIF = +SUPPLY VOLTAGE FORWARD DIRECTION
* VIB = +SUPPLY VOLTAGE REVERSE DIRECTION
* RQ#  -- EQUIVALENT CIRCUIT RESISTANCE OF Q(#)
* Q#EXP = EXPONENTIAL MODEL FOR TRANSISTION BETWEEN SATURATION AND CUTOFF
* TTIME -- SWITCHING TIME OF TRANSISTOR
* (NUMBERING INCLUDES THE FIVE VERSIONS FROM REF. 1)
* VERSION SIX -- THIS MODEL SIMULATES INSTANTANEOUS SWITCHING
* OF THE CURRENTS OF A BRUSHLESS DC MOTOR.
* THE WINDINGS ARE NOT TREATED INDEPENDENTLY AND THEIR
* CONTRIBUTIONS TO DEVELOPED TORQUE ARE TREATED AS SUPERPOSABLE.
* SINCE THE SUPERPOSITION RESULTS IN TWICE AS MUCH CURRENT FLOW
* AS A SINGLE LUMPED COIL, THE TOTAL CURRENT IS HALVED.

INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
```

```
 JM = 0.001, KB = 0.112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.740, TL = (96.,128)
PARAMETER VSAT = .4, RSAT= .02 , RCUT = 1.0E+4
NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
  A2 = J / B
  A3 = LA/(RA +RSAT)
  THRST = 0.0
  JFAC = 0.0
DYNAMIC
  VIF= 30.0 * STEP(0.0)
  VIB =-30.0 * STEP(0.0)
  VIN = VIF - VIB
  VIN1 = VIF - VEMF
  VIN2 = VIB + VEMF
  IPOS = (VIN1 - VSAT)/(RA+RSAT)
  INEG = (VIN2 + VSAT)/(RA+RSAT)
* LEG CURRENTS
  IMA = REALPL(0.0,A3,IA)
  IMB = REALPL(0.0,A3,IB)
  IMC = REALPL(0.0,A3,IC)
  DIADT = DERIV(0.0, IMA)
  DIBDT = DERIV(0.0, IMB)
  DICDT = DERIV(0.0, IMC)
  VA = IMA*(RA)+LA*DIADT+SIGN(VEMF, IMA)
  VB = IMB*(RA)+LA*DIBDT+SIGN(VEMF, IMB)
  VC = IMC*(RA)+LA*DICDT+SIGN(VEMF, IMC)
* VOLTAGES ACROSS TRANSISTORS
* NO DAMPER DIODES
  VQ1 = VIF - VA
  VQ2 = VA - VIB
  VQ3 = VIF - VB
  VQ4 = VB - VIB
  VQ5 = VIF - VC
  VQ6 = VC - VIB
* AVERAGE CURRENT TO MAKE MOTOR TURN
  IMT = (ABS(IMA) + ABS(IMB) + ABS(IMC))/2
  TM = IMT * KT
  TN2 = TN1 * (1.0/B)
  WM = REALPL(0.1,A2,TN2)
  WMRPM = WM * (30./PI)
  WMRPMR = WMRPM/N
  VEMF = WM * KB
  THETA = INTGRL(0.0,WM)
  THDEG = THETA * (180.0/PI)
  THCON = THRST
```

```
   PWR = WM * TM * .0070615

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.
PROCEDURE TN1=FWDBWD(VIN,TM,TL)
   IF(VIN.LT.0.0) GO TO 10
      TN1 = TM - TL
      GO TO 15
 10   TN1 = TM + TL
 15 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
      TS = JFAC * 360.0
      THRST = THDEG - TS
      IF(THRST.LT.360.0) GO TO 40
      JFAC = JFAC + 1.0
 40 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE SERVES SEVERAL PURPOSES.  FIRST, IT PROVIDES THE MODEL A
* MEANS OF APPLYING THE PROPER VOLTAGE TO THE APPROPRIATE WINDINGS WHICH
* SIMULATES COUNTERCLOCKWISE COMMUTATION.
* SECOND, IT SETS THE VARIABLES SE1 THRU SE3
* AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC

PROCEDURE IA,IB,IC,SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON,...
IPOS, INEG)
   IF(THCON .GE.180.) GO TO 45
   GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
   IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
   IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
   IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50   IA =  0.
      IB =  INEG
      IC =  IPOS
      SE1 = 1.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   51 IA =  IPOS
      IB =  INEG
      IC =  0.
      SE1 = 1.
      SE2 = 0.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   52 IA =  IPOS
      IB =  0.
      IC =  INEG
      SE1 = 1.
      SE2 = 1.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   53 IA =  0.
      IB =  IPOS
      IC =  INEG
      SE1 = 0.
      SE2 = 1.
      SE3 = 0.
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   54 IA =  INEG
      IB =  IPOS
      IC =  0.
      SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   55 IA =   INEG
      IB =   0.
      IC =   IPOS
      SE1 = 0.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   60 CONTINUE
  ENDPROCEDURE

  TERMINAL
    TITLE BASIC DC MOTOR SYSTEM
    TIMER FINTIM = .040, OUTDEL = .40E-4, PRDEL = .0004
    PRINT WM, VA, IMA, VB, IMB, VC, IMC, PWR
    LABEL TRANSISTOR VOLTAGE
    OUTPUT TIME, VQ1, VQ2, VQ3, VQ4, VQ5, VQ6
    PAGE XYPLOT
          END
          STOP
  ENDJOB
```

```
* VERSION SEVEN -- THIS
* MODEL SIMULATES THE SWITCHING LOGIC AND INSTANTANEOUS TRANSISTOR
* COMMUTATION OF A BRUSHLESS DC MOTOR CONTROLLED BY THE SWITCHING
* LOGIC PROCEDURE.
* THE WINDINGS ARE TREATED INDEPENDENTLY AND THEIR
* CONTRIBUTIONS TO DEVELOPED TORQUE ARE TREATED AS SUPERPOSABLE.
* SINCE THE SUPERPOSITION RESULTS IN TWICE AS MUCH CURRENT FLOW
* AS A SINGLE LUMPED COIL, THE TOTAL CURRENT IS HALVED.

INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.740, TL = (96.)
PARAMETER VSAT = .4, RSAT= .02 , RCUT = 1.0E+4
NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
  A2 = J / B
  A3 = LA/(RA +RSAT)
  THRST = 0.0
  JFAC = 0.0
DYNAMIC
  VIF= 30.0 * STEP(0.0)
  VIB =-30.0 * STEP(0.0)
  VIN = VIF - VIB
  VIN1 = VIF - VEMF - VSAT
  VIN2 = VIB + VEMF + VSAT
  RQ1 = FCNSW(SW1, RCUT, RCUT, RSAT)
  RQ2 = FCNSW(SW2, RCUT, RCUT, RSAT)
  RQ3 = FCNSW(SW3, RCUT, RCUT, RSAT)
  RQ4 = FCNSW(SW4, RCUT, RCUT, RSAT)
  RQ5 = FCNSW(SW5, RCUT, RCUT, RSAT)
  RQ6 = FCNSW(SW6, RCUT, RCUT, RSAT)
* VOLTAGE DIVIDER
  VAN = VIN1*RQ2/(RQ1+RQ2) + VIN2*RQ1/(RQ1+RQ2)
  VBN = VIN1*RQ4/(RQ3+RQ4) + VIN2*RQ3/(RQ3+RQ4)
  VCN = VIN1*RQ6/(RQ5+RQ6) + VIN2*RQ5/(RQ5+RQ6)
* CURRENTS BETWEEN LEGS
  IAB = (VAN - VBN)/(2*RA)
  IBC = (VBN - VCN)/(2*RA)
  ICA = (VCN - VAN)/(2*RA)
* INDIVIDUAL LEG CURRENTS
  IA  = IAB - ICA
  IB  = IBC - IAB
  IC  = ICA - IBC
* TIME CONSTANTS
  ATAU = LA/(RA + RQ1*RQ2/(RQ1+RQ2))
```

```
   BTAU = LA/(RA  +  RQ3*RQ4/(RQ3+RQ4))
   CTAU = LA/(RA  +  RQ5*RQ6/(RQ5+RQ6))
*  INDUCTIVE LEG CURRENTS
   IMA = REALPL(0.0,ATAU,IA)
   IMB = REALPL(0.0,BTAU,IB)
   IMC = REALPL(0.0,CTAU,IC)
   DIADT = DERIV(0.0, IMA)
   DIBDT = DERIV(0.0, IMB)
   DICDT = DERIV(0.0, IMC)
   VA = IMA*(RA)+LA*DIADT+SIGN(VEMF, IMA)
   VB = IMB*(RA)+LA*DIBDT+SIGN(VEMF, IMB)
   VC = IMC*(RA)+LA*DICDT+SIGN(VEMF, IMC)
*  AVERAGE CURRENT TO MAKE MOTOR TURN
   IMT = (ABS(IMA)  + ABS(IMB)  + ABS(IMC))/2
   TM = IMT * KT
   TN2 = TN1 *  (1.0/B)
   WM = REALPL(0.1,A2,TN2)
   WMRPM = WM *  (30./PI)
   WMRPMR = WMRPM/N
   VEMF = WM * KB
   THETA = INTGRL(0.0,WM)
   THDEG = THETA *  (180.0/PI)
   THCON = THRST
   PWR = WM * TM * .0070615

*  THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
*  DIRECTION.
PROCEDURE TN1=FWDBWD(VIN,TM,TL)
   IF(VIN.LT.0.0) GO TO 10
      TN1 = TM - TL
      GO TO 15
 10 TN1 = TM + TL
 15 CONTINUE
ENDPROCEDURE

*  THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
*  OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
*  SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
      TS = JFAC * 360.0
      THRST = THDEG - TS
      IF(THRST.LT.360.0) GO TO 40
      JFAC = JFAC + 1.0
 40 CONTINUE
ENDPROCEDURE


*  THIS PROCEDURE SERVES SEVERAL PURPOSES.  FIRST, IT PROVIDES THE MODEL A
*  MEANS OF APPLYING THE PROPER VOLTAGE TO THE APPROPRIATE WINDINGS WHICH
*  SIMULATES COUNTERCLOCKWISE COMMUTATION.
* SECCND, IT SETS THE VARIABLES SE1 THRU SE3
* AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  TECON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.
PRCCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCCN)
  IF(THCON .GE.180.) GO TO 45
  GO IC 46
45  THCON = THCON - 180.
46 CCNTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50 SE1 = 1.
    SE2 = 0.
    SE3 = 1.
    SW1 = 0.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 1.
    SW6 = 0.
    GC TO 60
 51 SE1 = 1.
    SE2 = 0.
    SE3 = 0.
    SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 0.
    SW6 = 0.
    GC TO 60
 52 SE1 = 1.
    SE2 = 1.
    SE3 = 0.
    SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 0.
    SW5 = 0.
    SW6 = 1.
    GC TO 60
 53 SE1 = 0.
    SE2 = 1.
    SE3 = 0.
```

```
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   54 SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   55 SE1 = 0.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   60 CONTINUE
ENDPROCEDURE
TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .0004, PRDEL = .0004
  PRINT WM, VA, IMA, VB, IMB, VC, IMC, PWR
  LABEL TRANSISTOR VOLTAGE
  OUTPUT TIME, VQ1, VQ2, VQ3, VQ4, VQ5, VQ6
       END
       STOP
ENDJOB
```

```
* VERSION EIGHT -- THIS
*MODEL INCORPORATES THE FINITE TRANSITION TIME FOR THE TRANSISTOR
*SWITCHES  AND IS OTHERWISE THE SAME AS VERSION SEVEN.
*THE WINDINGS ARE NOT TREATED INDEPENDENTLY AND THEIR
*TRANSIENT ELECTRICAL INTERRELATION IS SIMULATED, ALTHOUGH THE
*CONTRIBUTIONS TO DEVELOPED TORQUE ARE TREATED AS SUPERPOSABLE.
*SINCE THE SUPERPOSITION RESULTS IN TWICE AS MUCH CURRENT FLOW
*AS A SINGLE LUMPED COIL, THE TOTAL CURRENT IS HALVED.
INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.740, TLL= 128.
PARAMETER VSAT = .4, RSAT= .05, RCUT = 1.0E+4, TTIME = 1.0E-6
NOSORT
   BLP = BL/(N**2)
   JLP = JL/(N**2)
   J = JM + JLP
   B = BM + BLP
   A1 = LA / RA
   A2 = J / B
   A3 = LA/(RA +RSAT)
   THRST = 0.0
   JFAC = 0.0
METHOD STIFF
DYNAMIC
   VIF= 30.0 * STEP(0.0)
   VIB =-30.0 * STEP(0.0)
   VIN = VIF - VIB
   VIN1 = VIF - VEMF
   VIN2 = VIB + VEMF
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
*Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
*AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
*THE LIMITER
   Q1EXP = REALPL(1.0, TTIME, 1.0-SW1)
   Q2EXP = REALPL(1.0, TTIME, 1.0-SW2)
   Q3EXP = REALPL(1.0, TTIME, 1.0-SW3)
   Q4EXP = REALPL(1.0, TTIME, 1.0-SW4)
   Q5EXP = REALPL(1.0, TTIME, 1.0-SW5)
   Q6EXP = REALPL(1.0, TTIME, 1.0-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
   RQ1 = LIMIT(RSAT, RCUT, RCUT*Q1EXP)
   RQ2 = LIMIT(RSAT, RCUT, RCUT*Q2EXP)
   RQ3 = LIMIT(RSAT, RCUT, RCUT*Q3EXP)
   RQ4 = LIMIT(RSAT, RCUT, RCUT*Q4EXP)
   RQ5 = LIMIT(RSAT, RCUT, RCUT*Q5EXP)
   RQ6 = LIMIT(RSAT, RCUT, RCUT*Q6EXP)
   VAN = VIN1*RQ2/(RQ1+RQ2) + VIN2*RQ1/(RQ1+RQ2)
```

```
      VBN = VIN1*RQ4/(RQ3+RQ4)  + VIN2*RQ3/(RQ3+RQ4)
      VCN = VIN1*RQ6/(RQ5+RQ6)  + VIN2*RQ5/(RQ5+RQ6)
    * EQUIVALENT RESISTANCE
      REQAB = 2.*RA  + RQ3*RQ4/(RQ3+RQ4)  + RQ1*RQ2/(RQ1+RQ2)
      REQBC = 2.*RA  + RQ3*RQ4/(RQ3+RQ4)  + RQ5*RQ6/(RQ5+RQ6)
      REQCA = 2.*RA  + RQ1*RQ2/(RQ1+RQ2)  + RQ5*RQ6/(RQ5+RQ6)
      IAB =  (VAN  -  VBN)/REQAB
      IBC =  (VBN  -  VCN)/REQBC
      ICA =  (VCN  -  VAN)/REQCA
    * TIME CONSTANTS
      ABTAU = 2.* LA/REQAB
      BCTAU = 2.* LA/REQBC
      CATAU = 2.* LA/REQCA
    * LEG CURRENTS
      IMAB = REALPL(0.0,ABTAU,IAB)
      IMBC = REALPL(0.0,BCTAU,IBC)
      IMCA = REALPL(0.0,CATAU,ICA)
    * NET LEG CURRENTS
      IMA = IMAB - IMCA
      IMB = IMBC - IMAB
      IMC = IMCA - IMBC
      DIADT = DERIV(0.0, IMA)
      DIBDT = DERIV(0.0, IMB)
      DICDT = DERIV(0.0, IMC)
      VA = IMA*(RA)+LA*DIADT+SIGN(VEMF, IMA)
      VB = IMB*(RA)+LA*DIBDT+SIGN(VEMF, IMB)
      VC = IMC*(RA)+LA*DICDT+SIGN(VEMF, IMC)

    * VOLTAGES ACROSS TRANSISTORS
    * NO DAMPER DIODES
      VQ1 = VIF - VA
      VQ2 = VA - VIB
      VQ3 = VIF - VB
      VQ4 = VB - VIB
      VQ5 = VIF - VC
      VQ6 = VC - VIB
      IQ1 = FCNSW(SW1, .003, .003, IMA)
      IQ2 = FCNSW(SW2, .003, .003, IMA)
      IQ3 = FCNSW(SW3, .003, .003, IMB)
      IQ4 = FCNSW(SW4, .003, .003, IMB)
      IQ5 = FCNSW(SW5, .003, .003, IMC)
      IQ6 = FCNSW(SW6, .003, .003, IMC)
      PQ1 = VQ1 * IQ1
      PQ2 = VQ2 * IQ2
      PQ3 = VQ3 * IQ3
      PQ4 = VQ4 * IQ4
      PQ5 = VQ5 * IQ5
      PQ6 = VQ6 * IQ6
      PQTOT = PQ1 + PQ2 + PQ3 + PQ4 + PQ5 + PQ6
    * AVERAGE CURRENT TO MAKE MOTOR TURN
```

```
   IMT = (ABS(IMA) + ABS(IMB) + ABS(IMC))/2
   TM = IMT * KT
   TL = TLL*STEP(1.0E-3)
   TN2 = TN1 * (1.0/B)
   WM = REALPL(0.1,A2,TN2)
   WMRPM = WM * (30./PI)
   WMRPMR = WMRPM/N
   VEMF = WM * KB
   THETA = INTGRL(0.0,WM)
   THDEG = THETA * (180.0/PI)
   THCON = THRST
   PWR = WM * TM * .0070615
   IL = VIN/(2*RCUT)
   PWRDSS = 2.*VSAT*IMT + 4.*RCUT*IL**2
* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.
PROCEDURE TN1=FWDBWD(VIN,TM,TL)
   IF(VIN.LT.0.0) GO TO 10
     TN1 = TM - TL
     GO TO 15
 10 TN1 = TM + TL
 15 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
     TS = JFAC * 360.0
     THRST = THDEG - TS
     IF(THRST.LT.360.0) GO TO 40
     JFAC = JFAC + 1.0
 40 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE SIMULATES COUNTERCLOCKWISE COMMUTATION.
* IT SETS THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.
PROCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON)
   IF(THCON .GE.180.) GO TO 45
   GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
```

```
      IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
      IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
      IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
   50 SE1 = 1.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   51 SE1 = 1.
      SE2 = 0.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GC TO 60
   52 SE1 = 1.
      SE2 = 1.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   53 SE1 = 0.
      SE2 = 1.
      SE3 = 0.
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   54 SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
 55   SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
 60 CONTINUE
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .200, OUTDEL = .40E-4, PRDEL = .0004, DELMIN =1.0E-10
  FINISH THRST = 360.
  PRINT WM, WMRPM, THRST, VEMF, VAN, VBN, VCN, VA, VB, VC, ...
   IAB, IBC, ICA,...
   IMAB, IMBC, IMCA, IMA, IMB, IMC, IMT, DIADT, DIBDT, DICDT,...
   Q1EXP, Q2EXP, Q3EXP, Q4EXP, Q5EXP, Q6EXP, ...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6,...
   PQ1,PQ2,PQ3,PQ4,PQ5,PQ6,PQTOT, PWRDSS,PWR, ...
   IM, IL
  RANGE DELT
  LABEL MACHINE VOLTAGE AND CURRENT
  OUTPUT VA, IMA
  OUTPUT VB, IMB
  OUTPUT VC, IMC
* PAGE XYPLOT
        END
        STOP
```

```
* VERSION NINE --
* THIS MODEL IS ESSENTIALLY THE SAME AS VERSION EIGHT
* EXCEPT THAT THE DERIV FUNCTION IS ELIMINATED.
* THE RESULTING NUMERICAL SOLUTIONS ARE VIRTUALLY IDENTICAL.
* IF PROBLEMS ARE ENCOUNTERED WITH THE DERIV SUBROUTINE,
* SUBSTITUTION OF THE TECHNIQUES USED IN THIS MODEL MAY
* PROVE TO BE VALUABLE.
INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.740, TLL= 64.
PARAMETER VSAT = .4, RSAT= .02 , RCUT = 1.0E+4, TTIME = 1.0E-6
NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
  A2 = J / B
  A3 = LA/(RA +RSAT)
  THRST = 0.0
  JFAC = 0.0
METHOD RKS
DYNAMIC
  VIF= 30.0 * STEP(0.0)
  VIB =-30.0 * STEP(0.0)
  VIN = VIF - VIB
  VIN1 = VIF - VEMF
  VIN2 = VIB + VEMF
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
* Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
* AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
* THE LIMITER
  Q1EXP = REALPL(1.0, TTIME, 1.0-SW1)
  Q2EXP = REALPL(1.0, TTIME, 1.0-SW2)
  Q3EXP = REALPL(1.0, TTIME, 1.0-SW3)
  Q4EXP = REALPL(1.0, TTIME, 1.0-SW4)
  Q5EXP = REALPL(1.0, TTIME, 1.0-SW5)
  Q6EXP = REALPL(1.0, TTIME, 1.0-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, ...
  Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, ...
  Q5EXP=0.1, Q6EXP=0.1
  RQ1 = LIMIT(RSAT, RCUT, RCUT*Q1EXP)
  RQ2 = LIMIT(RSAT, RCUT, RCUT*Q2EXP)
  RQ3 = LIMIT(RSAT, RCUT, RCUT*Q3EXP)
  RQ4 = LIMIT(RSAT, RCUT, RCUT*Q4EXP)
  RQ5 = LIMIT(RSAT, RCUT, RCUT*Q5EXP)
  RQ6 = LIMIT(RSAT, RCUT, RCUT*Q6EXP)
  VAN = VIN1*RQ2/(RQ1+RQ2)  + VIN2*RQ1/(RQ1+RQ2)
  VBN = VIN1*RQ4/(RQ3+RQ4)  + VIN2*RQ3/(RQ3+RQ4)
  VCN = VIN1*RQ6/(RQ5+RQ6)  + VIN2*RQ5/(RQ5+RQ6)
* EQUIVALENT RESISTANCE
  REQAB = 2.*RA + RQ3*RQ4/(RQ3+RQ4)  + RQ1*RQ2/(RQ1+RQ2)
  REQBC = 2.*RA + RQ3*RQ4/(RQ3+RQ4)  + RQ5*RQ6/(RQ5+RQ6)
  REQCA = 2.*RA + RQ1*RQ2/(RQ1+RQ2)  + RQ5*RQ6/(RQ5+RQ6)
  VAB = VAN - VBN
  VBC = VBN - VCN
  VCA = VCN - VAN
  DIABDT =  (VAB - IMAB*REQAB)/(2*LA)
  DIBCDT =  (VBC - IMBC*REQBC)/(2*LA)
  DICADT =  (VCA - IMCA*REQCA)/(2*LA)
* LEG CURRENTS
  IMAB = INTGRL(0.0,DIABDT)
  IMBC = INTGRL(0.0,DIBCDT)
  IMCA = INTGRL(0.0,DICADT)
* NET LEG CURRENTS
  IMA = IMAB - IMCA
  IMB = IMBC - IMAB
  IMC = IMCA - IMBC
  VA = IMA*(RA)+LA*DIADT+SIGN(VEMF, IMA)
  VB = IMB*(RA)+LA*DIBDT+SIGN(VEMF, IMB)
  VC = IMC*(RA)+LA*DICDT+SIGN(VEMF, IMC)
* VOLTAGES ACROSS TRANSISTORS
* NO DAMPER DIODES
  VQ1 = VIF - VA
  VQ2 = VA - VIB
  VQ3 = VIF - VB
  VQ4 = VB - VIB
  VQ5 = VIF - VC
  VQ6 = VC - VIB
* AVERAGE CURRENT TO MAKE MOTOR TURN
  IMT =  (ABS(IMA)  + ABS(IMB)  + ABS(IMC))/2
  TM = IMT * KT
  TL = TLL*STEP(.001)
  TN2 = TN1 *  (1.0/B)
  WM = REALPL(0.1,A2,TN2)
  WMRPM = WM * (30./PI)
  WMRPMR = WMRPM/N
  VEMF = WM * KB
  THETA = INTGRL(0.0,WM)
  THDEG = THETA *  (180.0/PI)
  THCON = THRST
  PWR = WM * TM * .0070615
  IL = (VIF - VIB)/RCUT
  PWRDSS = 2.*VSAT*IMT + 4.*RCUT*IL**2

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING
```

```
*THE MOTOR'S DIRECTION.
PROCEDURE TN1=FWDBWD(VIN,TM,TL)
  IF(VIN.LT.0.0) GO TO 10
    TN1 = TM - TL
    GO TO 15
 10 TN1 = TM + TL
 15 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.
PROCEDURE THRST=RESET(JFAC,THDEG)
    TS = JFAC * 360.0
    THRST = THDEG - TS
    IF(THRST.LT.360.0) GO TO 40
    JFAC = JFAC + 1.0
 40 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE SETS THE VARIABLES SE1 THRU SE3
* TO LOGIC LEVELS 1 OR 0. THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF.
* THIS PROCEDURE SETS THE VARIABLES
* SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.
* THIS SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF
* THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.
PROCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON)
  IF(THCON .GE. 180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
  IF(THCON .GE.   0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE.  30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE.  60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE.  90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50 SE1 = 1.
    SE2 = 0.
    SE3 = 1.
    SW1 = 0.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 1.
    SW6 = 0.
    GO TO 60
 51 SE1 = 1.
```

```
      SE2 = 0.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   52 SE1 = 1.
      SE2 = 1.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   53 SE1 = 0.
      SE2 = 1.
      SE3 = 0.
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
   54 SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   55 SE1 = 0.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   60 CONTINUE
```

```
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .40E-4, PRDEL = .0002, DELMIN=1.0E-9
  RANGE  DELT
  PRINT WM, THRST, VEMF, VAN, VBN, VCN, VAB, VBC, VCA, VA, VB, VC, ...
   IMAB, IMBC, IMCA, IMA, IMB, IMC, IMT, DIABDT, DIBCDT, DICADT,...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6,...
   REQAB, REQBC, REQCA, ...
   TM, TL, WMRPM
  PREPARE WM, TM, WMRPM, THRST, VA, VB, VC, IMAB, IMBC, IMCA,...
   IMA, IMB, IMC, IMT, DIADT, DIBDT, DICDT,...
   VEMF, ...
   RQ1, RQ2, RQ3, RQ4,RQ5, RQ6
  LABEL PHASE A MOTOR VOLTAGE (9)
  OUTPUT TIME, VA
  PAGE XYPLOT
       END
  LABEL PHASE A MOTOR CURRENT
  OUTPUT TIME, IMA
  PAGE XYPLOT
       END
  LABEL BACK EMF VOLTAGE
  OUTPUT TIME, VEMF
  PAGE XYPLOT
       END
  LABEL MOTOR SPEED DEMONSTRATING COMMUTATION RIPPLE
  OUTPUT TIME, WM
  PAGE XYPLOT
       END
       STOP
ENDJOB
```

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